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Simulating fast electron beam melting with a parallel thermal free surface lattice Boltzmann method

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ABSTRACT

This paper introduces a three dimensional (3D) thermal lattice Boltzmann method for the simulation of electron beam melting processes. The multi-distribution approach incorporates a state-of-the-art volume of fluid free surface method to handle the complex interaction between gas, liquid, and solid phases. The paper provides a detailed explanation of the modeling of the electron beam gun properties, such as the absorption rate and the energy dissipation. Additionally, an algorithm for the construction of a realistic powder bed is discussed. Special emphasis is placed to a parallel, optimized implementation due to the high computational costs of 3D simulations. Finally, a thorough validation of the heat equation and the solid–liquid phase transition demonstrates the capability of the approach to considerably improve the electron beam melting process.

1. Introduction

Electron beam melting (EBM) is an additive manufacturing method used to produce metallic structures layer by layer from metal powder (Fig. 1). The latter is positioned on the starting plate included in the vacuum chamber and is melted by the electron beam gun. After a short time of solidification the powder hopper pushes the next powder layer on top and the EBM process starts again. Numerous products are generated by EBM, e.g., medical implants like hip joints or artificial spinal disks or components for aerospace and automotive industry.[1] The possibility to construct very complex structures which are strong and flexible is one of the most important advantages of EBM manufacturing. The target objectives of the 3D simulation of the EBM process are the acceleration of the building process and the improvement of the production accuracy. Therefore, a better understanding of the beam–powder interaction is necessary.

Based on a two dimensional thermal free surface lattice Boltzmann model [1] we develop a thermal 3D free surface lattice Boltzmann (LB) implementation where powder particles are taken into account. The model includes hydrodynamic physical effects, e.g., the flow of the melt pool as well as thermal effects, e.g., beam absorption, melting and solidification. However, 3D simulations require a high computational intensity and thus a thorough parallelization and optimization of the program is required. The implementation is integrated in the waLBerla framework (widely applicable lattice Boltzmann solver from Erlangen) which is used for solving problems in Computational Fluid Dynamics. waLBerla is extended by several thermal effects necessary for the simulation of the EBM process, e.g., absorption and solidification. The generation of metal powder

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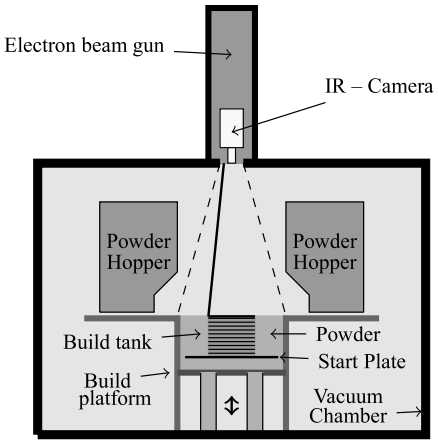

Fig. 1. EBM process.

particles, represented as rigid bodies, is supported by the physics engine pe framework. Special focus lies on the parallel implementation of all algorithms to take into account of high computational costs of 3D simulations.

Carefully chosen numerical tests are used to evaluate the EBM method and gain insight in their fundamental processes. For physical validation, numerical results of special scenarios are compared with experimental results. Hence, the scenarios cover various electron beam properties, e.g., different energy distributions, beam powers and velocities of the beam movements which can be specified individually for each scenario. For the simulations of melting domains of meaningful size these scenarios are implemented in parallel and have to be computed on supercomputers. Our results show the high potential of the thermal LB approach to understand and develop complex processes like EBM depending on thermodynamic as well as on fluid dynamic considerations.

The remainder of the paper is organized as follows. Section 2 explains the thermal free surface LB method where special attention is paid to cell conversions and solid–liquid phase transition. Subsequently, Section 3 focuses on the aspects concerning the modeling of the EBM process, i.e., the definition of the electron beam, the different absorption types and the generation of the powder particles. In Section 4 information about the two software frameworks waLBerla and pe is provided, followed by validation examples like the comparison of the analytical and numerical solution of the heat equation and the Stefan problem. Section 4 is closed with a numerical example of melting a spot in a powder bed where the behavior of the simulated melt pool is discussed. Finally, numerical aspects and targets of future work are described in Section 5.

2. Numerical methods

The governing macroscopic equations to simulate the incompressible transport equations for the EBM process are given by

$$\nabla \cdot \mathbf{u} = 0, \tag{1}$$

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

$$\frac{\partial E}{\partial t} + \nabla \cdot (\mathbf{u}E) = \nabla \cdot (k \nabla E) + \Phi, \tag{3}$$

where t denotes the time, $\mathbf{u}$ the velocity of the melt, p the pressure, ρ the density, ν the kinematic viscosity, k the thermal diffusivity, $\mathbf{g}$ the gravity and E the energy density. Moreover, Φ identifies the beam energy absorbed by the material.

For the numerical discretization of Eqs. (1) and (2) we use an isothermal 3D LB method (LBM). A thermal LBM is explained for the numerical treatment of Eq. (3) based on a multi-distribution approach where the energy density is modeled as a passive scalar. We briefly discuss advantages of this multi-distribution approach. For the treatment of the moving boundary between the melted metal and the vacuum in the EBM chamber we use a volume-of-fluid free surface approach. The idea of the free surface approach is shown before we conclude Section 2 explaining the liquid–solid phase transition and the regarding rules for cell conversions.

2.1. The LBGK model for hydrodynamics

The first lattice Boltzmann models were introduced as alternative numerical methods for hydrodynamic problems by [2] and can be seen as a discretization of the Boltzmann equation [3]. An improvement of LBM compared to its predecessor, lattice gas automata, is the existence of a particle distribution function (pdf). The pdf $f(\mathbf{x}, \mathbf{v}, t)$ indicates the probability of finding a particle with the macroscopic velocity $\mathbf{v}(\mathbf{x}, t)$ at position $\mathbf{x}$. The basic idea of the LBM [4,5] is to solve the Boltzmann

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