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Powder layer deposition algorithm for additive manufacturing simulations

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ABSTRACT

Powder bed fusion processes are additive manufacturing technologies, where parts are built up layer by layer in a powder bed. The highly complex geometries manufactured with these technologies are the main advantage and the difference to conventional technologies, where they are hardly machinable. Numerical models can replace the intensive and expensive trial-and-error principle to find suitable process parameters for the production of accurate parts.

This work presents a stochastic algorithm to generate a random powder bed for numerical simulations of powder bed fusion processes. The main focus is the efficient coupling of a classical discrete element approach to a grid-based solver used to simulate the melting process. The algorithm is implemented and validated in the range of common relative powder layer densities of powder bed fusion processes. The computational efficiency is demonstrated and finally, the complete coupling to a process simulation of the selective electron beam melting process is presented.

1. Introduction

The term additive manufacturing (AM) describes processing technologies of mainly layer-by-layer component fabrication by joining materials. Powder bed fusion (PBF) technologies are AM processes, where subsequent layers of powder are partially fused. Different technologies consolidate the material by sintering (selective laser sintering (SLS) [1]) or melting (selective laser melting (SLM) [1,2], selective electron beam melting (SEBM) [3,4]) initiated by induced heat energy of an electron or laser beam [5]. Depending on the material and its temperature, the powder particles are bounded by solid-state/chemical sintering or partial/full melting. The final properties and accuracy of the manufactured component are highly dependent on the quality of the single powder layers [6–10].

In the process cycle, a new powder layer is distributed by a powder delivery system, before the particles are joined. In this study, the powder delivery is explained using the SEBM process. An SEBM powder delivery system consists of a rake and two powder hoppers, as illustrated in Fig. 1. The rake moves slightly into the powder heap provided by the powder hoppers, whereby some particles are falling onto the other side of the rake. These particles are subsequently distributed by moving on the other side of the build tank, where the procedure is mirror-inverted repeated. This principle distribution mechanism is implemented by different powder feedstock and distribution devices for other PBF processes.

Numerical methods are commonly applied to understand and optimize different aspects of PBF processes [11] just like powder delivery, because they are hardly accessible by process observation. In literature, mainly two different techniques are used to model the powder particle settlement into a powder bed numerically. First, rain-drop models are used, where the position of each single particle within the powder bed is analytically computed consecutively. The second technique uses the discrete element (DE) method, where all powder particles are simulated simultaneously.

The easiest approach of modeling the powder delivery is to completely neglect the distribution process itself and solely describe the powder particle packing by a rain drop model [12,13]. After choosing a random horizontal position for each particle, the first contact with all previously settled particles is computed by a vertical trajectory. Subsequently, the particle is allowed to rotate to the next contacts until the minimum potential energy is reached. This model is successfully applied for a two- and three-dimensional simulations [6,14]. However, the final relative densities are commonly not adjustable and too high for PBF processes, where values between 40% and 60% are reasonable [15]. A solution for this problem is to delete single particles after layer generation to achieve the desired relative density [6]. However, this procedure generates artificial defects in the powder layer, which influence the final porosity since these defects can cause multi-layer channel faults [10,16].

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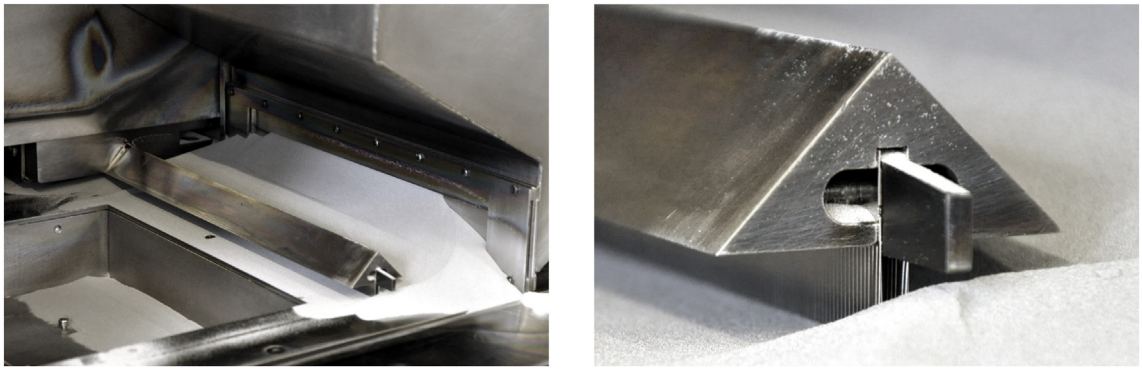

Fig. 1. Rake system of an SEBM machine. The rake consists of a triangular body equipped with two displaced rows of tines. For powder delivery, the rake immerses into the powder heap provided by the powder hoppers, whereby powder is falling onto the other side of the rake. Subsequently it moves to the opposite side and pushes the powder into the build tank.

The second approach is the DE method [17], where different implementations are present in literature. This method computes the forces between particles, distribution device and build chamber walls, and moves the particles according to Newton's equations of motion. The first model is a free fall model, where all powder particles are initialized and compact due to gravitational forces [18,19]. In the context of PBF, this method is applied to SLS of single layers including thermal sintering of the particles by the laser [20]. The second DE approach models the complex powder delivery process with additional cohesive non-contact forces, like van der Waals and electrostatic forces [21–23]. These simulations are performed to study the powder delivery process and how modifications on the powder, the rake geometry or process parameters can modify the final powder bed properties. The models are validated in comparison to experiments to predict improvements on the powder delivery process. A third model is a particle packing method which initializes particle nuclei randomly distributed within the desired volume and let them grow until a certain relative density is achieved [24,25]. Although this approach is modified from mono-dispersed particles to arbitrary size distributions, it is not able to ensure the correct final mean diameter of the size distribution. Since the algorithm stops, when the desired relative density is reached, the current size distribution represents the correct shape, but the mean diameter is presumably too small.

Despite these approaches we pursue a different target. Our goal is to develop a powder delivery algorithm, which efficiently generates a powder bed of a desired relative powder bed density for any PBF process. Furthermore, we aim a three-dimensional and parallel algorithm, which should be coupled to our mesoscopic simulation software for melting during PBF [11,26-28]. Recent investigations have demonstrated a major influence of PBF processes on the relative density of the powder bed [6–10]. Therefore, rain drop models are not investigated, due to limitations in adjusting the relative powder density and the sequential, non-parallel order of the algorithm. An important requirement on the powder delivery is the computational efficiency in comparison to the simulation of the melting process. Since full models of the powder delivery including the raking process are expensive stand alone simulations, they are also excluded. This is justified, because we are targeting a specific relative density of the powder bed rather than the correct physical mechanisms of powder layer formation. The particle packing methods are excluded because they can not guarantee the correct mean particle diameter once the relative density is reached. Therefore, we apply an optimized free fall DE model similar to [20], which reduces the computational effort and is well suited for parallelization. Since we couple the DE method with a grid based solver for melting, we add additional conversion steps from DE particles into the Cartesian grid. A further novelty is the application of multiple layers on top of partially molten layers. Therefore, we also present an approximation scheme for the current partially molten powder bed where the new powder layer is distributed on.

The paper is structured as follows: After the description of a numerical model for the powder particle characteristics, the DE approach is summarized in brief. Subsequently, the powder bed generation algorithm including the coupling of the powder layers to an additional grid based solver for melting is explained. After an appropriate choice of parameters, the algorithm is validated and the parallel efficiency is demonstrated. Finally, the manufacturing of a wall demonstrates the coupling of the powder bed distribution to the melting software.

2. Modeling powder properties

2.1. Powder properties

The powder delivery process mainly depends on the powder particle properties like shape, size distribution and flowability, which are adjusted by the production process. The characterizations in this work are examined with gas atomized Ti-6Al-4V powder particles sieved between 45 µm and 105 µm supplied by TLS, Germany. An appropriate parameter set during powder manufacturing avoids impurities inside the powder particles.

2.1.1. Particle shape

Atomization technologies produce almost spherical particles with a smooth surface topography. Two scanning electron microscope (SEM) images of the investigated powder with different resolutions are shown in Fig. 2. Although most of the particles are spherical, there are cylindrical or rod-like shapes (cf. Fig. 2 (a)) as well as agglomerates or satellites visible, where small particles are connected to larger ones (cf. Fig. 2 (b)).

2.1.2. Size distribution

The size distribution of spherical particles is characterized by their diameter and is measured by the light scattering method. The result is a cumulative relative frequency distribution $Q_0(d)$ defined by the ratio of the number of all particles smaller than the particle diameter d to the total number of particles in the sample [29]. The mean diameter of the whole size distribution d_{50} is defined, where the relative frequency reaches one half. The minimum and maximum diameter of the measurements are denoted by $d_{\min}$ and $d_{\max}$, respectively. The measured cumulative relative frequency distribution of the investigated powder ranges from 26 µm to 138 µm