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Particle-based simulation of powder application in additive manufacturing

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ABSTRACT

The development of reliable strategies to optimize part production in additive manufacturing technologies hinges, to a large extent, on the quantitative understanding of the mechanical behavior of the powder particles during the application process. Since it is difficult to acquire this understanding based on experiments alone, a particle-based numerical tool for the simulation of powder application is required. In the present work, we develop such a numerical tool and apply it to investigate the characteristics of the powder layer deposited onto the part using a roller as the coating system. In our simulations, the complex geometric shapes of the powder particles are taken explicitly into account. Our results show that increasing the coating speed leads to an increase in the surface roughness of the powder bed, which is known to affect part quality. We also find that, surprisingly, powders with broader size distributions may lead to larger values of surface roughness as the smallest particles are most prone to form large agglomerates thus increasing the packing's porosity. Moreover, we find that the load on the part may vary over an order of magnitude during the coating process owing to the strong inhomogeneity of inter-particle forces in the granular packing. Our numerical tool can be used to assist — and partially replace — experimental investigations of the flowability and packing behavior of different powder systems as a function of material and process parameters.

1. Introduction

Additive manufacturing can provide substantial benefits for part production in a broad range of applications compared to conventional machining [7]. By selectively melting layers of powder particles, parts of nearly arbitrarily complex geometries can be built directly from a three-dimensional (CAD) model [19], [47], [15], [25], [48]. In this process, the powder particles are melted into a mass of desired three-dimensional shape by using a laser or electron beam, which scans cross-sections generated from a CAD file on the surface of the powder bed. Once a cross-section is scanned, the powder bed is lowered by one layer thickness and a new layer of powder material is applied on top. The process is then repeated until completion of the part production [7], [15].

However, there are important open issues that need to be addressed in order to make this technology applicable for large-scale production [7]. In particular, the macroscopic characteristics of the produced part, such as porosity, are largely dictated by the geometric properties of the applied powder bed, which in turn depend on the mechanical behavior of the granular material during the coating process. The quantitative understanding of this behavior is, thus, one essential pre-requisite for developing optimization routes towards improved part quality and shorter production time [1,47]. Indeed, this behavior depends not only on the process parameters and the mechanical properties of the material constituting the particles, but also on the complex geometric shape of the individual powder particles.

Therefore, in order to reliably describe the mechanical behavior of the powder system during the additive manufacturing process, a particle-based numerical simulation tool, which accounts for a physical model for inter-particle forces as well as for a representation of the complex geometric shapes of the constituent particles, is required. In the present work, we develop such a numerical tool, based on the Discrete Element Method (DEM). We will show that our numerical tool can be useful to investigate geometric and dynamic aspects of the powder system employed in the manufacturing process, that are inaccessible to or difficult to investigate by means of experimental measurements.

In particular, we focus on the application process using a roller as coating device, which is a common application system in many additive manufacturing devices [22,15,18]. In the present work, we investigate the surface roughness of the deposited powder bed as a function of process speed, as well as the forces within the granular system emerging during the transport process. To the best of our knowledge, this is the first particle-based investigation of the load behavior on powder particles during powder application in additive manufacturing. The understanding of this behavior is one important prerequisite for modeling abrasion, plastic deformation and aging of the material used in the production processes.

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2. Numerical experiments

The powder application process is simulated using the Discrete Element Method, that is, simultaneously solving Newton's equations of translational and rotational motion for all constituent particles of the powder [13,35,20,41,45,50,36].

2.1. Model for the complex particles' geometric shapes

One challenge that needs to be addressed for the simulation of the application process is the modeling of particle shape. Fig. 1a shows an image of commercially available PA12 [38] powder particles used in the manufacturing process through selective laser melting [48]. As we can see, these particles display a diversity of geometric shapes that strongly differ from the round one. This can be also seen in the light microscope images displayed in the first row of Fig. 1b. It is well-known that granular systems constituted of non-spherical particles behave differently from particulate systems composed of spherical particles [36]. Therefore, the accurate representation of the particle shape is indispensable for the reliable simulation of powder application in additive manufacturing.

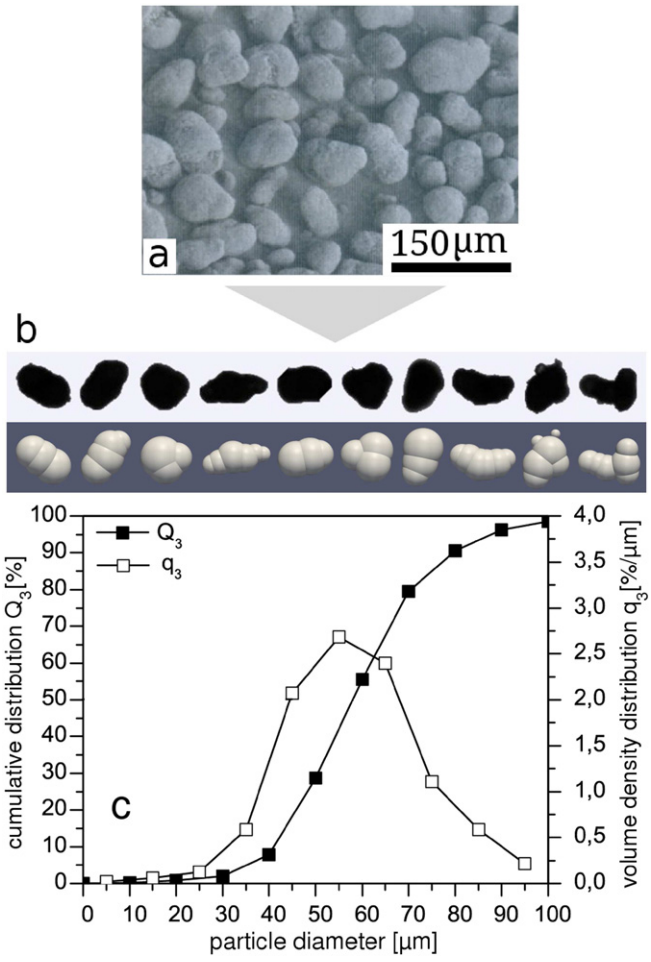

Fig. 1. (a) Commercially available PA12 powder particles of complex geometric shapes; (b) light microscope images of some of the powder particles (first row) and corresponding particle models using the multisphere method (second row) for implementation in the DEM. (c) cumulative distribution Q_3 and volume density distribution q_3 as a function of the particle diameter.
Courtesy of Maximilian Drexler, Lehrstuhl für Kunststofftechnik, Friedrich-Alexander-University of Erlangen-Nuremberg.

The complex geometric shape of powder particles is modeled here by means of the multisphere method, which consists of combining spherical particles of different sizes to approximate the non-spherical shape [13], [35], [28], [14], [12], [32]. In this method, each composite particle leads to a rigid body of complex geometric shape, whereas the total force on this body is computed by summing up the forces on all constituent spheres. Moreover, the resulting angular momentum of the complex particle is obtained from the total torque on all spheres with respect to the body's center of mass (see e.g. [28]). The second row in Fig. 1b shows images of composite particles constructed with the multisphere method to approximate the corresponding particle shapes displayed in the light microscope images. As we can see in Fig. 1b, a total of ten different particle samples were taken in the simulations. The chosen two-dimensional shapes (light microscope images of the real particles) shown in the first row of Fig. 1a have aspect ratio A — that is, length to width ratio — within the range $1 \leq A \leq 2$, which is representative of the modeled powder system. Moreover, some of the real powder particles are L-shaped while others have satellites attached to their surface, and thus we have also modeled sample particles with L-shape or satellites (see last two particles from left to right in both rows of Fig. 1b).

However, in order to apply the multisphere method for the simulation of particles of complex geometric shapes, the moment of inertia of the composite particle must be correctly calculated. In particular, spheres within a composite particle can overlap since they don't interact with each other, that is the interaction forces — described below — are not computed for pairs of beads within the same complex particle. In our simulations, we compute the mass and the moment of inertia of each complex particle by explicitly removing the contribution due to the overlap volumes between constituent spheres, using a recently derived model [32]. We note that the choice of the number and size of the constituent spheres used to construct the different multisphere particles in the simulations may have some influence on the results, which has not been investigated here. However, it has been shown that, for cohesive powder systems, the packing behavior of the granular material is mainly influenced by the size distribution and the attractive particle interaction forces [9], [33], which are described in the next section.

2.2. Model for the inter-particle forces

The interactions between spherical particles belonging to distinct composite particles are calculated by considering both contact forces and attractive particle interaction forces [36], [33].

The contact forces in DEM simulations can be described using a variety of models, each of which is suitable for a particular particle geometry and material behavior. Reviews of these models have been presented, for instance, by [41], [36], [27], and [28]. In our simulations, we assume viscoelastic interaction in normal direction [6] and employ a modified Cundall–Strack model [8] for computing the tangential component of the contact force [8]. The normal and tangential components of the contact forces read,

$$\vec{F}_n = \min\left(0, -\rho\xi^{3/2} - \frac{3}{2}A_n\rho\sqrt{\xi}\dot{\xi}\right)\vec{e}_n \tag{1}$$

$$\vec{F}_t = -\min\left[\mu\left|\vec{F}_n\right|, \int_{\text{path}} \frac{4G}{2-\nu}\sqrt{R_{\text{eff}}\xi}\,\mathrm{d}s + A_t\sqrt{R_{\text{eff}}\xi}v_t\right]\vec{e}_t \tag{2}$$

where

$$\xi = R_1 + R_2 - \left|\vec{r}_1 - \vec{r}_2\right| \tag{3}$$

is the compression of colliding particles, which have radii R_1 and R_2 and are at positions $\vec{r}_1$ and $\vec{r}_2$.