Effect of vibrations applied to the transport roller in the quality of the powder bed during additive manufacturing

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Abstract — Part of the optimization steps for the additive manufacturing is related to the correct understanding of the mechanical behavior of the powder used in the process. Numerical simulations through the Discrete Element Method (DEM) provide a useful means to investigate additive manufacturing process thus assisting and complementing experimental investigations. In particular, with the help to DEM simulations, it is possible to study particle-scale processes that are difficult to access experimentally. We investigate the characteristics of the powder bed deposited onto the manufactured part using a roller as the coating system. Furthermore, the non-spherical shape of real particles is also taken explicitly into account in the numerical simulations. A combination of translational velocity and sinusoidal vibration is used in the roller. The effect of varying the translational velocity, vibration frequency and amplitude in the density and roughness of the formed bed is investigated.

Keyword: DEM, Simulation, Particle Shape, Additive Manufacturing, Roller Vibration

1. INTRODUCTION

Rapid Prototyping is a term coined in the mid-1980s and used to describe a range of technologies that literally made prototypes of products in the early stages of development in a quick and automated manner. A variety of different techniques essentially combine planar layers of material, sequentially to form a 3-dimensional solid object [1]. An increasing demand to widen the field of application is noticeable, and rapid prototyping gradually is transferred to additive manufacturing. However, there are still restrictions, e.g. processing speed and product quality, in beam-based additive manufacturing processes like laser beam melting (LBM) [2].

In particular, understanding the mechanical behavior of the powder particles during the manufacturing process is essential for developing optimization routes towards improved part quality and shorter production time [3].

Discrete Element Method (DEM) describes the trajectory of each individual particle in the system along the time by means of integration of Newton’s equation of motion. Useful information to improve part quality and reduce production time can be obtained through numerical simulations by means of DEM, as particle dynamics are modeled as a function of material properties and particle shape [1,4,5,6].

DEM has been extensively developed [5,7,8] and validated [9,10,11,12] as a tool to investigate granular material flow. By choosing the correct collision parameters, particle size and shape the real granular behavior is captured [8,10,11,12].

In this study, a roller is used as coating device to spread a layer of particulate material over the surface to be sintered. This is a common application system in many additive manufacturing devices [13,14]. The quality of this layer of powder is investigated through numerical simulations by calculating the surface roughness of the deposited powder bed in the sintered area as a function of process speed. In addition, vibrations were applied to the roller and their effect in the bed quality was also investigated.

2. NUMERICAL SIMULATION

Powder deposition process was simulated using the discrete element method. Real shapes of commercially available PA12 [15] powder were approximated using a clump representation of the particles in the DEM simulations [3,16,17]. In addition, we extended our DEM library LIGGGHTS [18] to consider attractive particle interaction forces are also considered for bonded and non-bonded cohesive forces.

2.1. Particle shape model

Images of commercially available PA12 [15] powder were used as a base to recreate an approximated real particle shape. Sphere are “glued” together forming a clump of spheres, spatially distributed to capture most of
the real shape details. Center of mass and moment of inertia of clumped particles are calculated by means of a Monte Carlo integration, where a large sample of points are randomly generated on each sphere to detect overlapped regions and avoid including these regions twice in the calculations.

To represent the shapes of the real sample we used images of 10 different particles [14,15] to obtain clumps representation for our numerical simulations. Images of the particles and their corresponding DEM model are demonstrated in Fig. 1. All templates were equally used (10% in mass) in the simulations.

![Figure 1](image1.png)

Figure 1 – Images of particle templates used in numerical simulations. Top: Images of real particles in PA12 powder. Bottom: DEM representation of real particles by means of clumps.

Particle size distribution was experimentally measured for PA12 powder in [14]. Based on the experimental cumulative (Q3) distribution 5 different particles sizes were adopted in the numerical simulations as demonstrated in Fig. 2. This size distribution was applied to each of the 10 particle templates shown in Fig. 1.

![Figure 2](image2.png)

Figure 2 – Cumulative distribution (Q3) of particle size adopted in the DEM simulations.

2.2. Inter particle force models

Normal and tangential forces during collision between particles are calculated. A viscoelastic interaction is assumed in the normal direction [19] and a modified Cundall-Strack [20] model is adopted for computing the tangential component of the contact force [14]. The normal and tangential terms are given by:

\[
\tilde{F}_n = \min \left( 0, -\rho \frac{v^2}{2} - \frac{3}{2} A_n \rho \sqrt{\xi} \right) \tilde{e}_n
\]  

(1)

\[
\tilde{F}_t = -\min \left[ \int_{\text{path}} \frac{4G}{R_{\text{eff}}} \xi d + A_t \sqrt{R_{\text{eff}} v \xi} \right] \tilde{e}_t
\]  

(2)

\[
\xi = R_1 + R_2 - |\vec{r}_1 - \vec{r}_2|
\]  

(3)

\[
\vec{e}_t = \frac{(\vec{r}_1 - \vec{r}_2)}{|\vec{r}_1 - \vec{r}_2|}
\]  

\[
\vec{e}_n = \frac{(\vec{r}_1 - \vec{r}_2)}{|\vec{r}_1 - \vec{r}_2|}
\]

\[
\tilde{F}_{\text{JKR}} = 4 \sqrt{\frac{\pi \gamma \nu}{2(1-\nu^2)}} \tilde{e}_n
\]  

(5)

where \(\gamma\) is the surface energy density and \(a\) is the contact radius related to the overlap in the form:

\[
\xi = \frac{a^2}{R_{\text{eff}}} - \sqrt{\frac{8(1-\nu^2) \pi \gamma}{\nu}}
\]  

(6)

Due to the relatively small particle size non-contact van der Waals cohesive forces also have a significant influence in the flowability of the particulate material. These forces are incorporated in our DEM model in the following form:

\[
\tilde{F}_{\text{vdW}} = \begin{cases} 
\frac{4 \pi \gamma R_{\text{eff}}}{2} \tilde{e}_n, & \text{if } \xi > 0 \\
\frac{8 \pi \gamma R_{\text{eff}}}{2} \tilde{e}_n, & \text{if } -D_{\text{max}} \leq \xi \leq 0 \\
0, & \text{if } \xi < -D_{\text{max}}
\end{cases}
\]  

(7)

where \(D_{\text{min}} = 1.65 \text{ Å}\) is a parameter introduced to avoid the singularity of the Hamaker equation, and \(D_{\text{max}} = 1 \mu\text{m}\) is the maximal (cutoff) distance of the van-der-Waals interaction [14]. The intensity of this interaction is characterized by the Hamaker constant, \(A_H\), which is given by [14]:

\[
A_H = 24 \pi D_{\text{min}}^2 \gamma
\]

The importance of JKR and van der Waals terms in the numerical model was addressed in previous studies when comparing experimental and numerical solid packing fraction [6]. Parameters used for the contact and non-
contact force models in the DEM simulations are depicted in Table 1.

Table 1 – Parameters adopted in the models used in the numerical simulations.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particle material density</td>
<td></td>
<td>1000 kg/m³</td>
</tr>
<tr>
<td>Young’s modulus</td>
<td>Y</td>
<td>2.3x10^7 Pa</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>N</td>
<td>0.40</td>
</tr>
<tr>
<td>Coulomb’s friction coeff.</td>
<td>µ</td>
<td>0.50</td>
</tr>
<tr>
<td>Surface energy density</td>
<td>Γ</td>
<td>0.1 mJ/m²</td>
</tr>
<tr>
<td>Hamaker constant</td>
<td>A_H</td>
<td>0.2x10^-21 J</td>
</tr>
</tbody>
</table>

To validate the inter-particle force model, Ref. [6] compared experimental results for the solid fraction of fine polydisperse powders covering a broad range of particle sizes applied in additive manufacturing. As presented in Ref. [6], predictions from simulations agreed quantitatively very well with the experiments.

3. NUMERICAL RESULTS

A total of 12 simulations, each consisting of 20732 particles and 76229 spheres, were performed. Four different translational velocities were used for each of our numerical cases – 20 mm/s, 40 mm/s, 75 mm/s and 100 mm/s. In the first case no vibration was applied to the roller, in the second case a sinusoidal vertical vibration with amplitude of 25 µm and a frequency of 100 Hz was applied to the roller and in the third case a sinusoidal vertical vibration with amplitude of 25 µm and a frequency of 200 Hz was applied to the roller. In addition to translational velocity, in all cases a rotational velocity of 167 rpm was also applied to the roller.

System consists of a blade with a diameter of 2.5 mm. The width (Y direction) of the system is 1 mm and periodic boundary conditions are applied in the width direction. Material is initially poured to a reservoir, which is then lifted and the roller spread the particles over the particle bed and the sintered region. The system is demonstrated in Fig. 3.

![Figure 3](image_url)  
**Figure 3** – Simulation domain with indications of the components. Translation and rotation are applied to the roller, in addition to vibration in the second and third cases. Particles are poured in a reservoir and further spread over the powder bed and sintered regions.

The topography of the powder bed was obtained by computing the surface roughness $\delta$ of the deposited powder bed. This roughness is defined as the standard deviation of the height profile of the powder bed’s cutout — its projection onto the vertical plane parallel to the transport direction. Specifically, the projection of the powder bed’s cutout onto the xz-plane (see upper right-hand corner of Fig. 3 for coordinate system) defines a two-dimensional (longitudinal) profile, $h(x)$, associated with the powder bed. This height profile $h(x)$ is defined as the upper boundary of the surface of the powder bed projected on the xz-plane. The surface roughness, defined as the standard deviation of this profile, provides one measure that can be used to quantitatively describe the packing characteristics of the applied powder.

Roughness was calculated for each of the simulated cases. Three slices were applied in the Y direction and the mean roughness and standard deviation were calculated. Results for the first case (no vibration) is demonstrated in Fig. 4. Results for the second case (100 Hz vibration) is demonstrated in Fig. 5. Results for the third case (200 Hz vibration) are demonstrated in Fig. 6. In Fig. 7 all cases are plotted together without the standard deviation for better comparison.

![Figure 4](image_url)  
**Figure 4** – Surface roughness ($\mu$m) as a function of roller translation velocity (mm/s) for the case without roller vibration. Standard deviation is also plotted.
An increase in the roughness could be depicted with the increase in the translational velocity of the roller in all cases. This was already expected as reported in other studies [14]. Also an increase in the roughness was detected for all translational velocities when vibration was applied. This goes in the opposite direction of the expected result - a decrease in the roughness value with the application of vibrations. However, this counter intuitive effect can be explained when observing the powder bed and sintered region in more details. Powder compaction in the sintered region is limited to the reduced number of particles forming the next layer (2-3 particles) to be sintered. As a result, stress cannot be transferred to lower layers. This, indeed, leads to a high compression of individual particles in this region due to the vibration of the roller, instead of improving the compaction.

To investigate this possibility, we measured the compressive force in the powder bed, which remained constantly low in the case where no vibration was used. In addition to that, when 200 Hz vibration was applied, we depicted regions with zero force (no contact between roller and particles) as well as peaks of forces (when roller compresses the particles). Even the values of the peaks, however, remained relatively low as the large layer of powder (about 10 particles) transfers part of the energy from the top to the bottom particles and increase the compaction of the powder bed. These forces and the powder bed region are indicated in Fig 8.

When the roller crosses the sintered region, the particles have a limited capacity on transferring the energy from the roller to the bottom layers and increase compaction, as a few particles only (2 or 3 particles) compose the powder layer in the sintered region. As a results, particles store large elastic energy when the roller compresses them. This effect is much more evident in the cases with vibration by the sudden compression. When the roller loses contact to the particles, this elastic energy is transferred to kinetic energy and makes particles jump from their compact position. This is almost insignificant when no vibration is applied to the roller, but largely amplified when vibration is present. As a result, we found an increase in the roughness of the system. Forces in the sintered region are depicted in Fig. 9. When 200 Hz vibration was used, forces
reached values as large as 2000 µN, out of the scale of the graph.

![Graph showing compressive forces measured in the sintered region for the case without and 200 Hz roller vibration. Forces reach maximum values of the order of up to 2000 µN for the vibration case. Scale is 10 times larger in the Y axis when compared to Fig. 8 and limited to 700 µN for better comparison between cases.]

Figure 9 – Compressive forces measured in the sintered region for the case without and 200 Hz roller vibration. Forces reach maximum values of the order of up to 2000 µN for the vibration case. Scale is 10 times larger in the Y axis when compared to Fig. 8 and limited to 700 µN for better comparison between cases.

4. CONCLUSIONS AND NEXT STEPS

A system consisting of PA12 commercial powder was simulated in the powder deposition process. Real particle shape and inter-particle forces were incorporated to the numerical model. Four different velocities and three system configurations were tested: one without vibration, one using a vibration of 100 Hz and one with a vibration of 200 Hz. By calculating the roughness of each configuration we could observe an increase in the roughness with the increase in the translational velocity of the roller.

Interesting to note was the fact that vibration in the roller actually worsened the system by increasing the roughness. We were expecting an improvement in the values of roughness. This however, can be explained by the limited number of particles deposited in the layer to be sintered. These particles are over a solid (sintered) surface, which means that the compaction is limited to the thin layer of particulate material over this solid surface, corresponding to 2-3 particles in average.

Although improvement could be found by increasing the height of the powder layer over the sintered part, there are process restrictions to the height of the powder bed due to the melting process to be limited to a few particles layer. Also to manufacture a part with precise shape through additive manufacturing only thin layers of powder should be melted each time.

This study gave interesting insights into the effect of the roller vibration by comparing different simulation scenarios. However, there is still the need to carry a systematic validation through comparing the numerical results with experimental measurements. While the inter-particle force model has been successfully validated in Ref. [6] thereby leading to quantitative agreement between numerical and experimental predictions for the bulk solid fraction of different powder size distributions, the simulations of the coating should still be compared with experiments performed under similar conditions. Moreover, the present simulations do not include load of the coating system (downward pressure) on the powder bed, which is normally applied in the experiments even in the absence of vibration. Therefore, the results presented here should be tested with experiments without load, while our model should be further extended to include the pressure of the coating device on the powder. Moreover, we intend to perform measurements of the powder bed quality for a sequence of PA12 layer deposition.

After experimental validation, a systematic search will be performed changing amplitude and frequency of the roller. In addition to that, other vibration modes like lateral vibrations of the roller could improve compaction of the powder without the disadvantage of generating high compressive forces between the roller and the layer of powder to be sintered.

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