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New strategies for powder compaction in powder-based rapid prototyping techniques

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Abstract

In powder-based rapid prototyping techniques, powder compaction is used to create thin layers of fine powder that are locally bonded. By stacking these layers of locally bonded material, an object is made. The compaction of thin layers of powder materials is of interest for a wide range of applications, but this study solely focuses on the application for powder-based three-dimensional printing (e.g. SLS, 3DP). This research is primarily interested in powder compaction for creating membranes with specific properties.

In this paper, methods of powder deposition are discussed and experiments carried out using a specimen powder bed apparatus and a custom powder compaction device, using these methods (doctor blade, forward and backward rotating roller, double action roller) with various parameters. The model of powder compaction is verified in experiments. Insight is gathered to gain a better prediction of powder compaction.

Selection and/or peer-review under responsibility of Professor Bert Lauwers

Keywords: Rapid prototyping; 3DP; three dimensional printing; powder compaction;

1. Introduction

In powder-based rapid prototyping techniques, powder compaction is used to create thin layers of fine powder that are locally bonded. By stacking these layers of locally bonded material, an object is made. The compaction of thin layers of powder materials is of interest for a wide range of applications, but this study solely focuses on the application for powder-based three-dimensional printing.

The goal of this research is to formulate a set of rules, to deposit and compact dry powder material, with a demanded bulk density (defined as the mass of many particles of material divided by the total volume, including pore volume and voids, they occupy). By this, further research can be done in the area of ceramic microstructure three-dimensional printing, green part properties and ink penetration into the powder substrate. Where in most 3D applications, the highest level of compaction is desired, this is certainly not the case when creating membranes.

In both 3DP and SLS, thin layers (order 10-100μm, Cima [1]) of powder material are deposited. The difference between the two processes is the principle of bonding. In 3DP, the particles are (relative weakly) bonded by a liquid [1], as in SLS, the material is, as its name foretells, locally sintered [2].

The properties of the printed part depend among others, on the density of the powder substrate [3]. The degree of binder penetration in 3DP depends among others on the porosity or presence of voids in the powder substrate, which is directly related to the bulk density of the powder substrate.

Three methods of powder compaction are investigated in this research. The three are: a doctor blade, a counter-rotating roller and a forward-rotating roller. A combination of both, a doctor blade followed by a forward rotating roller, as proposed and (in a modified setup) investigated by Niino et al. [5] is also discussed.

In the following sections; methods of powder deposition are discussed and experiments are carried out using a specimen powder bed apparatus and a custom

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powder compaction device, using these methods with various parameters. A model of powder compaction is verified in experiments. The model's parameters are refined to gain a better prediction of powder compaction.

1.1. *Theory*

Before the experimental results are discussed, the theory on powder compaction using a roller, doctor blade or combination of the both is discussed. By this, not only a model for powder compaction is described, but also various influences on the compaction process are identified and discussed.

1.1.1. Assumptions

Throughout this research, the following assumptions are made or points of interest are taken into account, in order to simplify the model and indicate possible sources of interference.

- ☐ The density of the powder in the powderbed or powder container is assumed to be constant in respect to the position (X, Y, Z) of the powder bed. The effect of displacement of layers has been investigated by Lee et al. [7]. They observed that the vertical position of a layer is relatively secure within the bulk region of a part.
- ☐ The powders are assumed to be homogenous in the bulk density of the powder as it is deposited, in X-, Y- and Z-direction.□ Szucs et al. [8] have shown that the accuracy of commercial ZCorp 3DP machines is not constant in respect to X-,Y- and Z-orientation.
- ☐ The shape of the particles is not taken into account. It is known that disk-shaped particles tend to behave different than spherical particles. The mentioned study on the subject of powder layer position accuracy by Lee et al. [7] indicate that disk-shaped particles form a more dense powder bed, using the same conditions.
- ☐ The lower limit of the thickness of new layers is among others determined by the mean diameter of the particles. Generally, the particles must be smaller than the layers printed [10] due to issues of powder flow and spreadbility.
- ☐ Vibrations cause the powder to compact, but its effect is omitted in the model.

1.2. *Flowability of powder*

All methods of powder deposition and compaction need to overcome one common problem: the flow properties of the powder must be temporarily improved to distribute the powder evenly across the powder bed [11]. But after individual particles are positioned and orientated, flow properties must be decreased to an absolute minimum to avoid disturbance of the powder bed and provide a solid powder layer for the printing process. But, flowability is not an inherent material property [12]. Flowability is the result of the combination of material physical properties that affect material flow and the equipment used for handling, storing, or processing of the material.

1.2.1. Doctor blade

The simplest form of powder deposition and compaction is done using a doctor blade. A doctor blade, as showed in Figure 1, is a thin blade, which presses continuously against the surface with a sweeping action, distributing powder along the build platform, but no real compaction occurs. The only parameter that can be altered is the layer height. The individual particles arrange themselves in the, energetically, most efficient way [12].

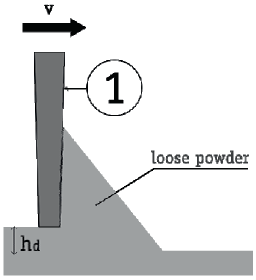

Figure 1 Schematic representation of a doctor blade (1)

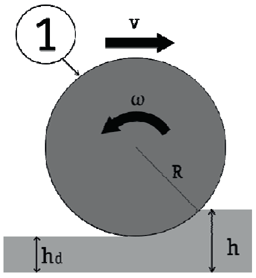

Figure 2 Schematic representation of a counter-rotating roller (1)

Hence the fact that the blade will not be geometrically perfect straight and smooth, unevenness' of the blades surface are transferred over the complete powder bed, possibly disturbing the deposited layer (with height h_d).

1.2.2. Counter-rotating roller

The most used method of powder deposition and compaction in commercial powder-bed three-dimensional printing machines (e.g. ZCorp) is done using a counter-rotating roller, as shown in Figure 2. During the deposition and compaction process, the roller traverses over the powder bed while the roller rotates in opposite direction. This rotation stimulates the flowability of the powder in front of the roller, as powder in the roller gap is compacted due to the traversing motion.

A model of the counter-rotating roller has been derived by Shanjani et al. [4]. Note that in this model, there is an amount of loose powder and not a 'bow wave' in front of the roller, as in reality occurs.

According to this model, the main parameters of the counter-rotating compaction process are (also shown in Figure 2): powder layer thickness, roller radius, roller contact pressure, roller angle and friction between of both roller-powder and powder- powder.

The density as described by Shanjani et al. [4], does not depend on neither linear nor rotational velocity of the roller. But, for low values of these velocities, the counter-rotating roller will act as a doctor blade.

By solving the differential equation, using an Euler forward integration scheme, the influence of the main parameters can be investigated. Shanjani et al. [4] provided values for some of the parameters, but did not mentioned how these values were obtained (for example the friction coefficient of the powder-roller and powder-powder interface).

To limit the scope of this research, the results from Shanjani et al. are not reproduced and discussed. But according to their model, the roller radius has a very strong influence on the density

1.2.3. Forward-rotating roller

Current literature shows no interest in compaction of powder by a forward-rotating roller. Due the forward motion of the roller, powder is compacted in the roller gap. Compared to the counter-rotating roller, compaction level is much higher [5]. But, the forward-rotating roller method is prone to disturbance of the new powder layer.

As powder is compressed under a forward-rotating roller, lumps of powder arise, that stick to the roller, leaving craters in the new layer of powder. As the presence of craters on the powder bed's surface is disastrous for the printing result, this should be avoided at all times. In order to still create a powder bed with a high velocity, the compaction process is slightly altered, as will be discussed in the next section.

1.2.4. Combination of doctor blade and forward rotating roller

As mentioned in the previous section, due to the high compression under a forward-rotating roller, some powder will stick to the roller, leaving craters in the new layer of powder. The level of compression is determined by the amount of loose powder in front of the roller. Niino et al. [5] proposed and investigated a double action roller, which has also been devised before [1]. In this process, first, a layer of powder is deposited using a counter-rotating roller, the build bed is raised, and the roller rotates forward over this relative loose powder.

For ease of operation and time savings, their method is adapted in this study, deploying a doctor blade for the deposition of the relative loose powder (also briefly mentioned by Niino et al. [5]). A schematic representation of this process is shown in Figure 3.

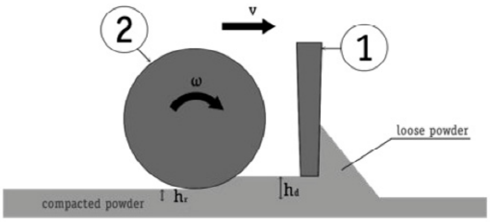

Figure 3 Compaction process by combination of doctor blade (1) and forward-rotating roller (2)

The disadvantages of the doctor blade (low level of compaction and disturbance of the new layer) are compensated by the forward-rotating roller, whose disadvantage is compensated by the limited amount of loose powder in front of the roller.

2. Experimental

Current literature shows no interest in measured bulk density of powder in three- dimensional printers using various conditions. An appendix of Lee et al. [7] shows a fractional factorial analysis, revealing only relationships. Their investigated parameters are: layer thickness, traverse speed, rotation speed, moisture level of the powder, roller vibration frequency, roller vibration amplitude and spreading excess. For small particles (±10μm), layer thickness and traverse speed have the largest influence on the bulk density.

In this study, a number of experiments are carried out to investigate the bulk density of powder by various methods, under various conditions. First the measurement setup is discussed, then material characterisation of the powder is discussed and finally, the measurements setups and the results are presented.

2.1. Measurement setup

2.1.1. Powder container

The powder is contained by the powder container, shown in Figure 4. This aluminum apparatus embodies a steel piston (h6H7) connected to an adjustment wheel via fine metric thread (pitch 0.5mm) that acts as a lead screw, driving the build piston.

Figure 4 Powder container

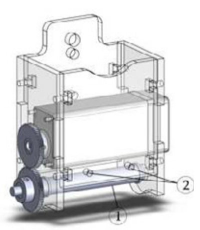

Figure 5 FabCompactor with roller (1) and mounting point for the doctor blade (2)

The build cylinder has a diameter of 40.55mm. Marks at 72° angle on the adjustment wheel indicate a linear displacement of the piston of 0.10mm.

2.1.2. Fab@Home/X,Y,Z-table

To enhance reproducibility of the measurements, all movements (except moving the build piston) are automated. A Fab@Home Model 2 rapid prototyping machine [13] is used as an X, Y, Z-table with an auxiliary motor for roller rotation, instead of the standard syringe tool.

The powder container is placed by hand on a marked spot and aligned every measurement to ensure its top surface is parallel to the Y-axis of the Fab@Home machine. The Fab@Homes Snap Motors are controlled using the ACI interface [14], over a serial port.

2.1.3. FabCompactor

The standard Fab@Home syringe tool is replaced for custom roller propulsion, as shown in Figure 5. The FabCompactor is attached to the Fab@Home's tool connector, enabling alignment of the tool in respect to the powder container. The distance and angle of the FabCompactor to the powder container can be adjusted.

2.1.4. Rollers & doctor blade

For the experiments, two different rollers and one doctor blade are used. The rollers, with diameter of 12.0mm and 22.0mm, are hand polished to reduce surface roughness. The surface roughness (R_a) has been determined by interferometric surface roughness measurement. The surface roughness of the 22mm roller is 380nm (±60) and for the 12mm roller 220nm (±40).

The doctor blade has a straight blade of 0.5mm thick.

2.2. *ZCorpTM ZP131 material characterisation*

All measurements are carried out using a single powder; commercially available ZCorp ZP131 [15]. According to its Material Safety Data Sheet, it contains the following components: Plaster which contains crystalline silic (50% – 95%), vinyl polymer (2% – 20%) and sulfate salt (0% – 5%).

2.2.1. Particle size distribution

The particle size distribution of the powder, ZCorp ZP131, is analysed using a Malvern Mastersizer 2000 [16], the result is shown in Figure 6. The particle size of the powder is distributed between 0.4µm and 120.0µm, with a mean particle size of 46.33µm.

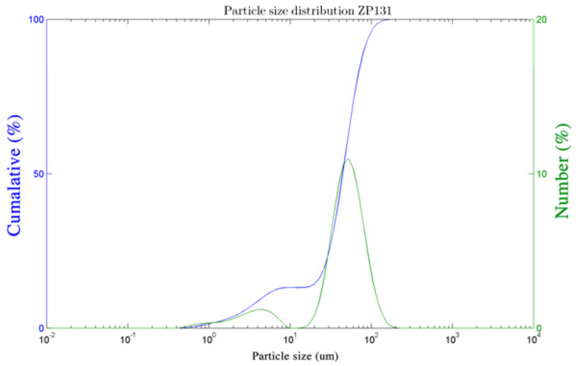

Figure 6 Particle size frequency and cumulative size frequency of ZCorp ZP131

2.2.2. Density ZCorp ZP131

The tapped density gives the upper limit of the compaction of the powder during compression.

The ZP131 datasheet indicates the density of the powder: 1.3 to 3.0 gr/cm^3 [15]. The measured tapped density (10 times, 10mm) of the ZP131 powder is 1.242gr/cm^3. The ultimate density, achieved by compressing the powder, is 1.374gr/cm^3.

2.2.3. *Particle shape (SEM)*

As mentioned earlier, the shape of the particles has significant influence on the compaction of the powder; both in terms bulk density and green part properties as isotropic behaviour.

The shape of the ZP131 powder has been determined by SEM imagery, using a Neoscope [18]. Figure 7 shows a 200 times magnification of the powder particles. The presence of two main particle sizes is legible, as is concluded from the particle size distribution.

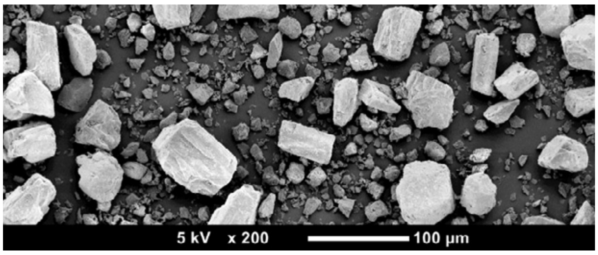

Figure 7 NeoScope image of ZP131 (magnification 200x)

3. Measurement

The execution of a single measurement goes as follows; the apparatus is cleaned to remove any leftover powder. Then, the apparatus is filled with a certain amount of powder and tapped and wiped. The apparatus with powder is weighted (*scales resolution: 0.01gr* [14]) and the displacement is measured with a calliper (*resolution 0.05mm*).

After that, the apparatus is filled with powder, layer by layer, using the Fab@Home to move the FabCompactor around. After 50 layers, it is weighted again and after the powder is removed, the displacement is measured.

4. Measurement results

The measurements, as discussed in the previous section, are carried out 5 times for every setup for the sake of reproducibility. The measurement data is plotted in box plots for every setup, indicating the mean, standard deviation and the upper and lower limit of the measurement.

The following setups are used, with according layer thicknesses:

Compacting device	**Layer thickness**
Counter-rotating roller	*0.1, 0.2, 0.3mm*
Forward rotating roller	*0.1, 0.2, 0.3mm*
Doctor blade	*0.1mm*
Doctor blade + forward rotating roller	*0.1, 0.2, 0.3mm*

Besides the measurement of the bulk density of the powder, a visual inspection of the powder surface is made. The results are discussed quite brief.

4.1.1. Counter-rotating roller

As shown in Figure 8, the density of the powder has a clear dependency with both roller diameter and new layer height. Small roller and large new layer height achieve the lowest level of compaction. The highest compaction can be achieved using a big roller and thin layers. The counter-rotating roller leaves an even and flat surface.

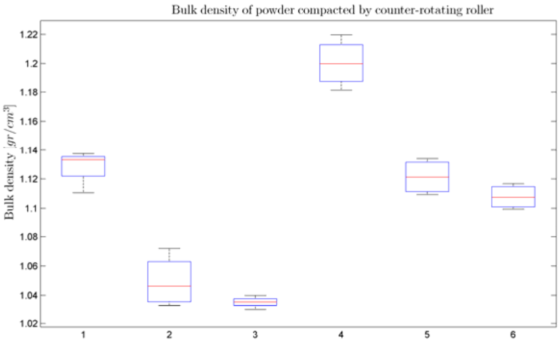

Figure 8 Bulk density of powder compacted by counter-rotating roller (1: Diameter roller:12mm new layer height 0.1mm 2: 12mm, 0.2mm 3: 12mm 0.3mm 4: 22mm 0.1mm 5: 22mm 0.2mm 6: 22mm 0.3mm

4.1.2. Forward rotating roller

Figure 9 shows the bulk density of the powder as compacted by a forward rotating roller. Only three successful measurements could be made as all other setups resulted in a useless powder surface, full of craters and drag.

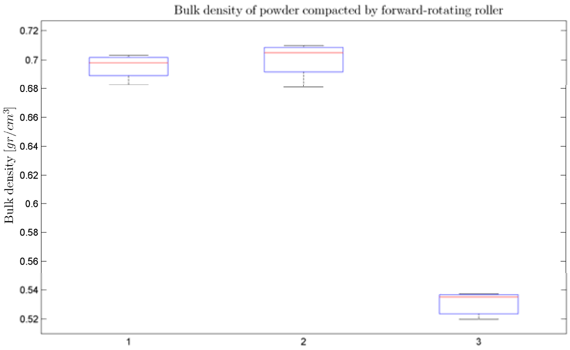

Figure 9 Bulk density of powder compacted by forward-rotating roller *(Diameter roller 12mm) (1: 160rpm 0.2mm, 2: 80rpm 0.2mm, 3: 40rpm 0.2mm)*

4.1.3. Doctor blade and combined

The bulk density achieved by doctor blade and combined doctor blade and forward-rotating roller are shown in Figure 10. As indicated by Niino et al. [5], the maximum compaction factor (the ratio of the height of the powder deposited by the doctor blade over the height of the powder compacted by forward-rotating roller) is 2.0. Higher compaction factors cause failure such as craters and drag of the powder bed. Therefore, the maximum pre-deposited layer by the doctor blade is 0.2mm high, while the roller is set at 0.1mm.

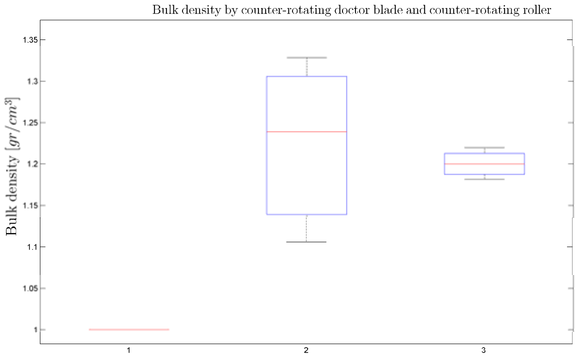

Figure 10 Doctor blade + forward rotating roller *(1: doctor blade 0.1mm, 2 doctor blade 0.2m + FWD roller (12mm) 0.1 3: doctor blade 0.2mm FWD roller (12mm) 0.1m)*

5. Conclusions

Strategies for powder compaction for powder based rapid prototyping have been discussed and experiments have been carried out. The methods include; doctor blade, counter-rotating roller, forward-rotating roller and the combination of a doctor blade with forward-rotating roller. Using various setups, these methods were tested using a specimen apparatus.

Two aspects of interest were recorded: the bulk density of the deposited powder and the surface quality of the deposited powder. Both influence the properties of the three- dimensional part (whether 3DP or SLS) and are of interest for creating porous membranes by powder based rapid prototyping.

The highest bulk density (1.2gr/cm^3) with the best surface quality was achieved using a counter-rotating roller with a diameter of 22mm. The combination of a doctor blade and forward-rotating roller is promising for a high density, but its setup must be refined to prevent distortion (craters, drag) or the powder surface. The lowest density is achieved by doctor blade, although the surface quality is moderate using that compaction method.

Using the measurement results, the setup of a future 3DP or SLS machine can be adjusted to deposit a powder with a desired bulk density, in order to create porous membranes. Hence the bulk density of deposited powder depends on the powder, mentioned measurement results are only valid for gypsum with the same particle size distribution. The identified relation between process parameters and the bulk density will still hold though.

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