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Open source powder based rapid prototyping machine for ceramics

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Abstract

3DP (Three Dimensional Printing) technology is one of the SFF (Solid Freeform Fabrication) technologies which have recently come into the spotlight due to its adaptability to various applications. However, commercial 3DP machines are limited as to the use of building material, without voiding the warranty on the machine.

At the same time, a rise in domestic rapid prototyping machines is observed, but none of these machines use the 3DP process. Therefore, an open source 3DP machine is designed and built. In this study, the machine is discussed and the first experiments are carried out to create ceramic (alumina and zirconia) membranes with specific physical properties.

The purpose for developing this machine was opening up the opportunity to investigate printing ceramic membranes and reactors. Were, contrary to many other applications, maximal compaction of the powder during deposition is not desirable, to maintain an open structure the walls of the printed object. The machine is able to deposit the powder with adjustable bulk density, which is used to alter the properties of the membrane. The design of the printer (drawings, electronic layout, software) is publicly released under an open source license, free for others to adapt, build and use, e.g. in academic research.

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

Keywords: Rapid prototypes; Open source hardware; Three Dimensional Printing; Manufacturing systems

1. Introduction

Over the last few years, we have seen an explosion in the personal 3D printer market. Many companies offer machines to consumers. These are, however, mostly based on the same 3D printing process; Fused Deposition Modelling (FDM). This limits the suitable materials to thermoplastics. No present machine has employed the three-dimensional printing (3DP) [1] process which uses powder materials (e.g. gypsum, plastics, ceramics) and a liquid binder.

In 3DP, an object is built layer-by-layer, using an inkjet printer that deposits droplets of binder the shape of a particular cross-section of the part to be produced, onto a bed of powder. Then, a roller or scraper adds a layer of powder atop the previously bound layer, and the process repeats until the part is complete [1,2].

In order to expand the scope of personal 3D printing technology and foster experiments with the 3DP process, a new machine should be developed deploying this powder-based process. The commercially available 3DP machines (Z Corporation, South Carolina, USA) are expensive and can only use a limited number of expensive and proprietary powder materials. While a significant strength of 3DP is the wide range of potentially suitable materials, including polymers, metals and ceramics[3], or any other depositable powder material with particle size in a suitable range [3]. Printing on a ceramic substrate in order to create membranes with specific properties, is investigated in this paper.

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2. Purpose

The main reason for investigating the direct inkjet printing of ceramic membranes is that the shape of the final product can be optimised for reactor performance and is not limited by constraints set by classical membrane reactor manufacturing techniques. Another advantage of using inkjet-based printing processes is that customised ceramic membranes can be manufactured without expensive mechanical finishing; there is no need for the use of specialised tooling and the time between the design of a reactor and the manufacturing thereof is minimised. The desired active surface area of the membranes varies from 30 – 100m^2/g, while the porosity is 30 – 40%.

The 3DP process properties can be fully varied; powder density, the way of powder compaction (e.g. counter-rolling, forward-rolling, double action, etc.), amount of binder liquid, print resolution and new layer height.

3. Specifications

The technical requirements and wishes have been set up on the basis of user requirements and wishes.

- Maximum size printed parts 100 x 100 x 100mm. When margins are taken into account for the stability of powder, this results in a build platform of 150 x 150 x 125mm.
- Adaptable bulk density of the powder. Research [5] has shown that the easiest way to change the bulk density is to alter the new layer height. In order to print the ceramic membranes with specific properties, the printer has to be able to deposit powder with various densities and altering the new layer height is the main method that will be incorporated to achieve this.

Technical wishes

- The machine design should be elegant and robust.
- Limit the number of (advanced) tools needed to build the machine.
- Enhance ease of assembly.
- Building the machine should be possible with limited resources, less than approximately €800).
- Enhance ease of use (i.e. preparing, using and cleaning).
- Minimise the space required and volume taken by the machine.

4. Design philosophy

With regard to the user requirements and wishes, some issues are impossible to incorporate into a metric for the technical specifications. In order to use these requirements and wishes during the design process, a 'design philosophy' is set up. This design philosophy acts as a guide during the design process.

- The number of parts will be kept to a minimum.
- Identical parts will be used wherever possible.
- Parts will be made as simple as possible, i.a. for mistake-proofing (Poka-yoke)
- Non-structural parts will be "off-the-shelf" (OTS) wherever possible. This ensures that substitution of similar OTS parts should require a minimum number of changes to the design. Modifications to OTS parts should be avoided.
- Accuracy of the machine is obtained by machining, not on the basis of the material.
- Structural parts are preferably cut by laser.

5. Overall design

The designed and constructed machine is shown in Figures 1 - 3. The machine consists of two bins (*stock and build*) containing the powder. To deposit a new layer of powder on top of the build piston, the stock piston is raised and the build piston lowered. Powder from the stock bin is then moved by a counter-rotating roller from the stock bin to the build bin.

When a new powder layer is deposited, the particles are locally bonded. An inkjet printer head is attached to a two-axis Cartesian gantry. The tooling is modular, i.e. a laser can be mounted to adapt the machines for the Selective Laser Sintering (SLS) process.

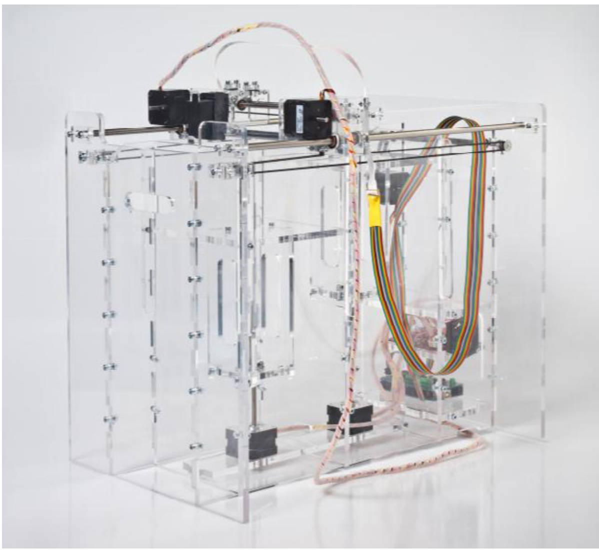

Figure 1 The Mode 0.1 Pwdr machine

The machine is assembled in about four hours. Soldering the custom electronics, connecting and routing all the wires takes about another four hours.

Building the Pwdr Model 0.1, as shown in the Figures 1-3, costs €973.97, including laser cutting. A full specification and bill of materials can be found on the project GitHub page[a].

5.1. Structure

The machines chassis and structural parts are laser cut from Acrylic plate material. To achieve a certain amount of robustness and prevent deformations, the chassis and pistons (*number of 22 parts*) are made of 8mm thick Acrylic. All other structural parts are 5mm thick (*number of 24 parts*).

The individual Acrylic parts are connected using T-bolt connectors. To enhance the assembly process, the parts are provided with protuberances that fit like jigsaw puzzle pieces, ensuring that the parts only fit in one way.

5.2. Positioning

Positioning of the gantry and pistons is done using stepper motors (Nanotec GmbH & Co, Munich, Germany). The motors are controlled in an open loop manner, i.e. there is no position feedback.

The piston positioning is done by linear positioning drives. The travel per step (*16 step microstepping mode*) is 0.625µm, with a thrust of 200N [4].

The rotational movement of the steppers is transformed by pulleys and timing belts into a linear movement for the Cartesian gantry. Integrated tensioners lower the hysteresis and ensure proper functioning. The travel per step of the gantry (both x- and y-direction) is 18.85µm, when micro stepping is in 8 step mode.

5.3. Powder handling

The powder material is deposited by transferring it from the stock bin (*moving up*) to the build bin (*moving down*) by a counter-rotating roller, propelled by a stepper motor (Nanotec GmbH & Co, Munich, Germany), via a timing belt. The process of depositing a new layer of power takes ± 30 seconds.

The bulk density of the powder in the build bin is adjusted by altering the new layer height; this method has been demonstrated in research [5,6]. The roller designed can also deposit the powder in a forward-rotating or a double-action manner. Other ways to adjust the bulk density are to alter the roller diameter and friction [5].

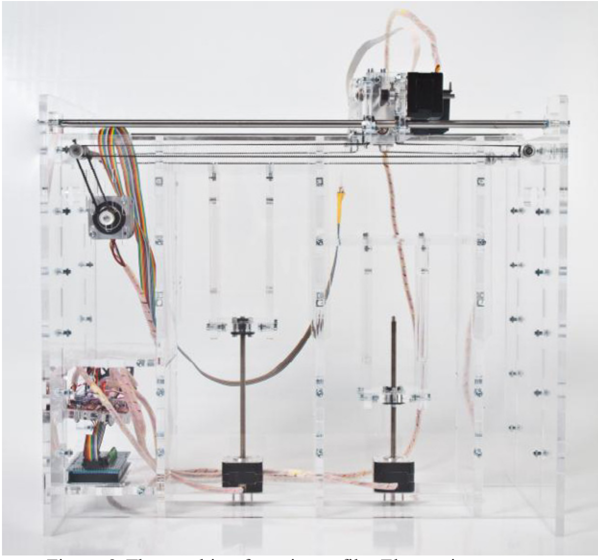

Figure 2 The machine from in profile. Electronics compartment bottom left. Y-stepper top left. Linear position drives and pistons centre and X-gantry top right.

5.4. Binder deposition

Binding the powder is done by depositing liquid binder on top of freshly deposited layers of powder. Deposition is done using a Hewlett-Packard C6602A inkjet cartridge (Hewlett-Packard Company, Palo Alto, United States), shown in Figure 3. The cartridge has 12 nozzles in a printing resolution of 96DPI, with an average drop size of 160pL [7]. This cartridge is chosen because the control (pulse widths and voltage) is known [8]. The cartridge is controlled by a custom proto shield for the Arduino microcontroller (discussed further on).

Another reason to opt for the C6602A cartridge is the fact that it can easily be refilled with custom binders. A mixture 20:80 ethanol and water has been used successfully. Printing a single layer of a part takes ± 60 seconds for a circular part with a diameter of 30mm (*otherwise depending on the amount of 'black'*).

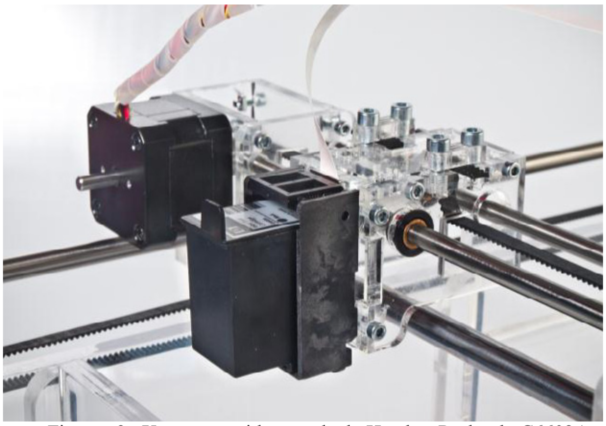

Figure 3 X-gantry with attached Hewlett-Packard C6602A cartridge and roller

5.5. Electronics

The electronics are composed of open source components where possible. The main unit is an Arduino Mega 2560 microcontroller (Arduino, arduino.cc), running the firmware of the printer. The microcontroller communicates with a client PC via bi-directional USB communication.

Attached to the Arduino are: the custom proto shield to control the print head, three EasyDriver stepper motor drivers (Brian Schmalz, United States) for the X,Y and roller steppers and two Big EasyDriver drivers (Brian Schmalz, United States) for the two linear position drives.

The stepper drivers and the proto shield have their own power supply. The stepper drivers are connected to a modified ATX power supply (Fortron, FSP Group, Taiwan) of which only a 12V line is used. The print head is powered by a domestic 24V power supply.

5.6. Software

The software section can be divided into two parts: the firmware that controls the machines actuators and handles the printing process; running on the Arduino microcontroller and the software; for pre-processing and monitoring the print process, running on the users' PC.

Tasks performed by the firmware include; controlling the steppers, sending out pulses for the print head, communicating with the PC via serial line and the reading and processing of the print files from an SD card during a print job.

The client software, written in Processing[b], slices the 3D STL file of the part and processes it into a printable format. These print files (*one for each layer, binary format*) are stored on an SD card, which is inserted in the proto shields SD shield. Starting a print job is also done in the client software. Prior to printing, the gantry and pistons can be manually jogged to e.g. fill the bins with powder. The print process can be monitored using the client software in which the progress is shown.

6. Results

The machine designed has been built and tested. Firstly, the accuracy of the machine has been determined.

6.1. Accuracy

The machine's positioning repeatability was determined by measuring the actual displacement, using a micrometer (Digimatic Indicator 543-250B, Mitutoyo, Takatsu-ku, Japan).

The accuracy of the Y-axis was determined by moving a pre-described number of steps to and from. If no hysteris, backlash or other inaccuracies are present in the system, the micrometer should read out a displacement of null. The average was 7µm, with a standard deviation of 52µm. The X-direction of the gantry can move with a repeatability of 5µm. The pistons, driven by the lead screw, exhibit a repeatability of 23µm.

The accuracy of the printer allows it to print in resolution of 96DPI, which is sufficient for most applications.

6.2. Print results

So far three materials have been used in the machine; gypsum (ZCorp ZP 131), alumina (AKP-15) and zirconia (TZ-2Y). The latter are used to produce ceramic membranes.

The initial tests to create membranes were performed with available stock material. These materials are not the best-suited material for creating membranes using 3DP due the particle size and shape. Furthermore, the ceramic materials are sintered at relative low temperatures to retain fine pores for the membranes.

6.2.1. ZCorp ZP 131

To proof the machine's functioning, the powder used first was a proven material, ZCorp ZP 131 powder [11], used in commercial 3DP machines. The powder, containing mainly gypsum, has a measured mean particle size of 47µm (Mastersizer 2000, Malvern, Worcestershire, UK) in a rather angular shaped. The ZP 131 is deposited in layers of 120µm (±23 µm) and bonded using the standard inkjet ink from the C6602A cartridge (*12 drops per spot*). A custom binder of 20% ethanol and 80% water has also been successfully used. The ethanol is added to decrease the viscosity for the inkjet head [10].

After printing and drying inside the powder bed, the part is fixated in resin to increase structural stability. The green part and the fixated part are shown in Figure 4. As can be seen in this figure, the powder is well-bonded and the shape is quite accurate, although sharp edges tend to break off very easily.

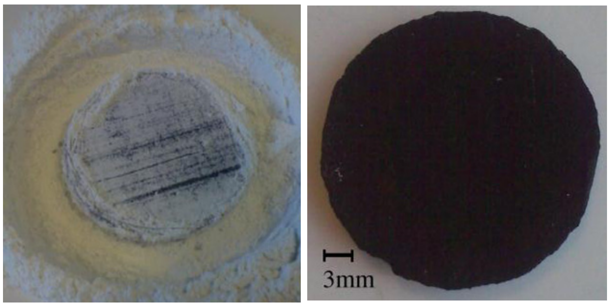

Figure 4 (left) Green gypsum part is excavated in powder bed and (right) fixated gypsum part (diameter 28mm)

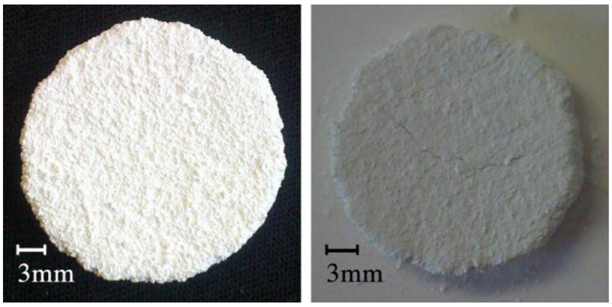

Figure 5 (left) Sintered alumina part (diameter 27mm) (right) sintered alumina-zirconia part (diameter 23mm)

6.2.2. Ceramics

Two ceramic materials have been used for the creation of membranes: alumina (AKP-15) and zirconia (TZ-2Y). As mentioned, these are not the best-suited material to create membranes with, but were available in stock. The dwell temperature during sintering is relatively low to retain small pores for the membranes.

6.2.2.1. Alumina AKP-15

The first material tested to make ceramic parts is AKP-15 alumina powder (Sumitomo Chemical, Tokyo, Japan). The mean particle size lies between 0.6 and 0.8µm, which means that it would be very hard to deposit dry [9], nonetheless, it was tried.

The particles tended to agglomerate and therefore the powder was very hard to deposit in a thin, uniform and smooth layer. As agglomerates of ±0.5mm are present, the minimum layer height is 0.3mm, but still, unevenness occurs and a rough powder surface arises.

The inkjet ink was used as a binder and worked well (*15 drops per spot*), after printing and some drying (at least 2 hours), the excess powder could be removed easily, though this needed to be done with care. The green parts are very vulnerable and especially sharp edges break off easily. Green parts were sintered at 1150°C and 1200°C with a dwell time of 2 hours (heating and cooling rate 2°C/min). During sintering, the binder is burned and only alumina remains.

Sintering for 1 hour at 1100°C gave a very brittle and unusable result. This sample was re-sintered for 2 hours at 1150°C. For both, the heating and cooling rate was 2°C/min.

A photograph of a sintered part is shown in Figure 5 (left). The diameter of the green part is 27mm and after sintering, almost no shrinkage is observed, apart from breaking little particles from the edges. Sintering at higher temperatures would increase stability of the ceramic parts, but would eliminate the desired small pores for the membranes.

6.2.2.2. Zirconia TZ-2Y

The zirconia used is agglomerated and has a mean particle size in the order of 50µm. The flowability of the powder is very high due the particle size and shape. One of the results of this is that the powder seeps out of even the slightest gap.

But on the other hand, this allowed the powder to deposit very well and in very thin layers (70µm has been achieved). On the downside, the binding of the powder with the standard HP ink is very poor. The green part breaks very easily during excavation.

ZCorp ZB 61 [11] binder was deposited on a small batch of zirconia in order to test the binding properties of this liquid. But even after a few hours of drying, the part created in this way looks bonded, but shatters at the slightest touch, lacking any structural cohesion. This binder is not applicable for the zirconia used. Future research will focus on a binder for zirconia.

6.2.2.3. Alumina and zirconia

To join the advantages of the alumina (*good powder-liquid bonding*) and zirconia (*good powder deposition)*, a mixture of the two is used. Equal weight amounts of alumina and zirconia are mixed thoroughly.

Binding was tested by depositing a few drops of binder on the powder mixture: a structurally coherent green part was formed.

When the machine was filled with the powder mixture, it was observed that the bigger alumina agglomerates cumulate in front of the roller. It has been ensured that these agglomerates are not deposited where the part is printed. A layer height of 110µm (±23µm) has been used and the powder is bonded using standard ink (*15 drops per spot*). After printing and drying, a relatively stable part can be excavated from the powder bed.

After sintering at 1500°C (heating and cooling rate 2°C/min) with a dwell time of 2 hours, a fragile part remains, shown in Figure 5 (right), which is damaged by the slightest touch. Future work has to be done to improve the quality of the sintered part.

7. Conclusions

The past few years, an emergence of open source solid freeform fabrication machines has observed. But none of them used the 3DP printing process, which opens the opportunity to experiment with various materials like plasters, ceramics, plastics and metals.

In order to accelerate the spread and development of powder based (e.g. 3DP, SLS) research, we have developed an open-source, low-cost personal 3DP system kit, which is called the Pwdr Model 0.1. The current kit design has a parts cost of roughly €900, requires only basic hobbyist tools and skills to assembly and use and can be used to deposit almost any powderous material and bind it with a liquid binder.

All the work (design, electronics) has been released under a Creative Commons Attribution-NonCommercial 3.0 Unported Licence. Besides, the machine deploys existing open source solutions for the electronics. The accompanying soft- and firmware has been released under the GNU/GPL license[c]. So far, three Pwdr machines have been build and used worldwide.

The machine has been used to print parts from gypsum, alumina, zirconia and a mixture of the latter. Binding is done by standard inkjet ink, but a custom mixture of water and ethanol has also been demonstrated.

Successful printing has been demonstrated using ZCorp ZP 131 powder, which results in a structurally coherent green part that can be fixated using resin.

The ceramic materials, alumina and zirconia gave varying results. The applied alumina (AKP-15) is very fine and therefore difficult to deposit in a thin layer, as agglomerates arise, resulting in a very course powder bed. Nonetheless, green parts were printed, with enough structural cohesion to excavate the parts and sinter them. The resulting alumina parts are very coarse and exhibit a rough surface.

The zirconia (TZ-2Y) has a larger particle size, and can be deposited in very thin layers. But, neither the inkjet ink, nor the custom mixture of water and ethanol or ZCorp ZB 61 liquid, could bind the powder to a rigid green part.

By combining the alumina and zirconia (50:50 in weight), a well depositable and bondable powder is created. Sintering the green parts resulted in a fragile, ceramic part, to be handled with great care.

Future work includes implementing improvements for Model 1.0, improve the quality of the sintered alumina-zirconia parts and experiment further with materials for ceramic membranes and experimenting with novel materials and applications. Due the low price, the machine is ideal for academic research.

Footnotes

[a] http://pwdr.github.com
[b] www.processing.org
[c] http://www.gnu.org/copyleft/gpl.html

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