

A novel approach to additive manufacturing: screw extrusion 3D-printing

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Abstract

This paper presents a novel approach of screw extrusion based 3D printing of thermoplastic materials. In contrast to the well-known extrusion based 3D printing technology Fused Deposition Modeling™ based on thermoplastic filament extrusion, granules are used as raw-material in a plastic processing screw, melting the plastic and depositing it at the required locations. The system is designed to overcome some limitations of the filament based process e.g. the need for a thermoplastic filament as feed material, which needs to be produced with a narrow production tolerance with respect to the nozzle diameter to prevent blocking and especially the limited range of commercially available materials which can be processed. The presented system is controlled by an open architecture based CNC-controller, programmed in such a way that it easily can be adapted and extended with new advanced control systems modules, systems to improve product quality.

Keywords: 3D-Printing, Additive Manufacturing, extrusion based 3D printing

1. Introduction

Rapid Prototyping, Rapid Manufacturing, Solid, Freeform Fabrication, 3D printing are well-known names for the production technologies that nowadays are grouped in the generic name additive manufacturing (AM), according to ASTM F2792-12a [1], subdivided in different subcategories according to the type of bulk material [2]. 3D printing, as presented in this work, is a subgroup of these processes fabricating objects through the deposition of a viscous material using a print head, nozzle or another printing technology [1].

The first AM-processes were limited to the rapid production of visual prototypes (rapid prototyping) to understand the shape of a designed component or a system. Thanks to the increasing interest and technological evolution, the improved dimensional accuracy achievable and properties of end materials, those production processes are nowadays also used for the production of single or small series of functional products.

Manufacturing of an object by AM starts from a digital surface model (.stl-file) of the object, that can be generated from a CAD model or 3D scan data. The data is processed by specific software, which divides the model into slices, depending on the layer resolution of the process. Then a hatching profile is applied to each slice as infill structure for the object. The construction starts by sending the processed data to the selected AM-process, which builds the object layer upon layer by joining material. Afterwards, a finishing step is mostly applied to remove the supporting structure (sacrificial material) and smoothing out the layered texture of the surface.

The paper presents the development of a novel approach for 3D printing of a broad range of thermoplastic materials. In contrast to the popular Fused Deposition Modeling (FDM™), based on the extrusion of a thermoplastic filament commonly ABS, PLA or PC, a designed three-section plastic processing screw is applied in a print head to overcome some limitations of the FDM™-process, e.g. a limited range of materials, the filament fabrication, This print head is mounted on the Cartesian frame of a retro-fitted coordinate measuring machine (CMM).

The print head and positioning of the system is controlled by an in-house developed real-time and FPGA based CNC-controller (computer numerical control), replacing the out-dated analogue controller of the CMM according to the actual standards, to ensure a position accuracy of a few μm . The open-architecture based CNC-controller allows the easy modification of the controller and the possibility to extend the controller with new modules for quality control of the process.

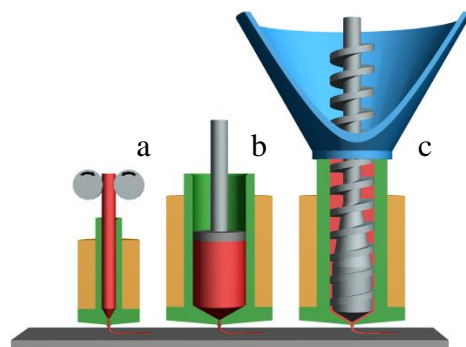


Fig. 1. Overview extrusion based 3D printing principles: (a) Filament based extrusion, (b) Syringe based extrusion, (c) screw based extrusion

2. Extrusion Based 3D printing

Extrusion based 3D printing processes fabricate objects through the deposition of material using a print head with nozzle. In this case objects are produced by heating the thermoplastic material into a visco-elastic melt that is extruded and deposited layer upon layer. In figure 1 an overview is given of the presented extrusion principles for producing objects with thermoplastic materials which are up to now not commonly available for AM: a) the well-known FDM™ -principle, b) syringe based extrusion and the presented screw based extrusion.

2.1. Filament based 3D printing

The popular commercially available filament extrusion based 3D printing process, Fused Deposition Modeling™, is shown in Figure 1.a. A spooled filament of a thermoplastic polymer is fed into the liquefier using a pinch feed mechanism [3]. The incoming solid filament acts as a plunger to push and extrude the liquefied polymer through the nozzle [4]. This extruded polymer is deposited according to the pattern generated from the 3D model on the build platform or the previous layer. Once a layer is processed, the building platform is lowered a layer thickness and a new layer can be deposited.

The fed material shaped in a filament, is produced by a polymer extrusion process, which requires a certain amount of material to fill the extruder and starting-up the filament extrusion production. In comparison to conventional extrusion, the filament will be produced to a very tight diametric tolerance which can not be achieved in conventional extrusion processes [5, 6]. Since the filament based 3D printing machine drive pushes the filament feedstock through the liquefier, a variation in diameter may cause blocking. A filament with a diameter that is too large will block the system (figure 2.a.), a filament with a diameter that is too small will not touch the wall of the extruder and will cause material rising between the wall and filament (fig 2.b). Further drawbacks of this process are buckling [4, 7, 8] (Fig 2.c) and slippage of the filament on the pinch wheel [7], causing an interruption of the building process and requiring intervention from the operator [3, 5, 6].

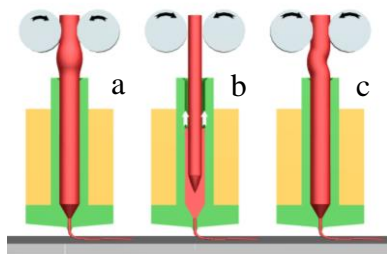


Fig. 2. Filament extrusion: problems caused by the filament: a), b) improper diameter filament, c) buckling

FDM objects are commonly made in acrylonitrile butadiene styrene (ABS), sometimes blended with polycarbonate (PC) to improve mechanical properties [9]. Also some engineering plastics are available with superior thermal and mechanical properties (for example polyphenylsulfone, PPSF/PPSU) [9, 10]. Beside these materials, some producers can deliver machines able to process polylactic acid (PLA), a biodegradable polymer. Nevertheless, very little effort has been made to develop and adapt the filament extrusion to process a broad range of thermoplastic materials as fed materials [11]. The limited availability of commercial polymer fed materials is therefore seen as a major shortcoming of the filament based 3D printing process.

2.2. Syringe based 3D printing

To overcome the limitations of the filament based extrusion process, as described in the previous paragraph, especially in terms of amount of material used for the extrusion of the fed materials and the range of the materials that can be processed, a solution was found in the syringe based extrusion process, as shown in figure 1.b. This configuration makes typically use of materials that solidify due to a chemical solidification, commonly used for biochemical applications where biocompatibility is required.[3]. A reservoir is filled with the material and heated to the processing temperature. A force or displacement controlled plunger pushes the material out of the reservoir according to the generated path from the 3D model

A proof of concept of a syringe based extrusion system tailored for polycaprolactone (PCL) was worked out at KU Leuven, Campus De Nayer, as shown in figure 3.

Main advantages of the system in comparison to the filament based system are the limited amount of material that is required to be fed into the system in granular shape and the low complexity of the construction. The granular shape is the common shape for raw thermoplastic material before it is formed into an object.

Despite of the satisfying results of the system, there are some disadvantages to syringe based printing.

- After a time at elevated temperature the material in the syringe will undergo thermal degradation, resulting in poor material properties.
- A difference in melt viscosity was noticed during processing caused by an inhomogeneous temperature distribution inside the barrel.
- During the production of large objects, the syringe needs to be refilled repetitively causing interruptions in the building process, cooling down of the partial printed product and syringe, resulting in a poor adhesion between the influenced layers [12].

- Due to air in the syringe, the extrusion process will be interrupted and in the processed material air encapsulations are found.

Because of the disadvantages indicated additional developments were carried out as explained in the next section.

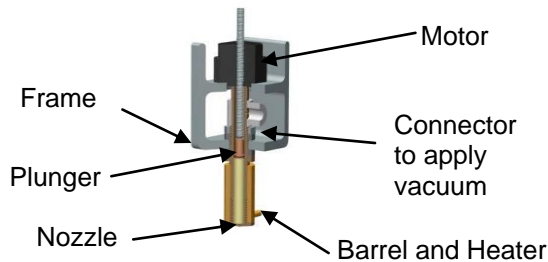


Fig. 3. Tailored syringe process for PCL

2.3. Screw based 3D printing

A solution for the above mentioned problems, especially the limited range of available materials, could be found in a three-section screw based extrusion process, as commonly used in the plastic processing industry to create continuous fixed shaped profiles. Figure 1.c. shows the principle of the screw based extrusion process specifically modified for the 3D printing process, as developed at the KU Leuven, Campus De Nayer.

Thermoplastic polymer granules, which are as mentioned before the typical shape for thermoplastic bulk material, are fed into the hopper and transported to the nozzle by the three-section screw. Heat is applied to soften the polymer granules into a viscoelastic melt. Pressure build-up by the screw-geometry, is needed to expel trapped air between the granules and to overcome the backpressure induced by the shape of the nozzle, acting as the die for the extrusion process.

This extrusion based 3D printing system offers a number of benefits:

- Commercially available granules can be fed directly into the barrel.
- A continuous process can be realized.
- A broad range of polymer as there are polypropylene (PP), polyethylene (PE), polystyrene (PS), polylactic acid (PLA), Polycaprolactone (PCL), ... materials can be processed, increasing the application area of 3D printed objects.
- The polymer suffers from less thermal degradation due to the homogeneous melting process and the small amount of melted polymer.

The complex design and construction of the required three-section-screw is a setback for the implementation, but this type of screw is required to avoid trapped air in the polymer melt, preventing interruption of the extrusion [7,8,11]. Figure 4 presents the screw extruder unit as designed. Besides the screw, barrel and nozzle also a frame for mounting the print head on the

retrofitted frame of the CMM is applied. Furthermore three heaters, in total 2 kW, are added to assist the melting process of the thermoplastic material.

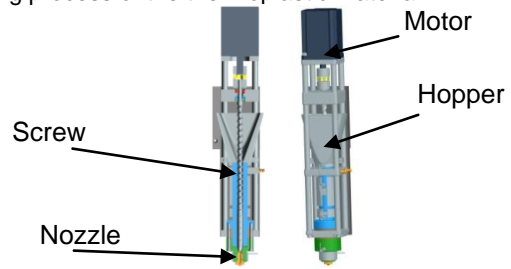


Fig. 4. Design of the screw extruder unit

3. Open architecture CNC controller

The presented screw extrusion based print head is mounted on a retrofitted coordinate measuring machine (CMM). The rigid marble Cartesian frame is reused, to guarantee a solid system. In combination with the original precision optical encoders a positioning accuracy of 3µm can be achieved. (Figure 6). The original CNC-controller of the CMM was outdated and replaced by a new real time and FPGA based CNC-controller, in-house programmed according to the open architecture CNC approach. In contrast to the common CNC controllers, that can be considered as black box application, open architecture based CNC controllers can easily be adjusted and extended to the needs of the machine, process, etc. independent of the machine were the controller is applied.

Where the real-time system is used for the interpretation and interpolation of the tool paths, the man machine interface and the closed coupling between the velocity of positioning and the speed of extrusion, the FPGA handles the position control of the Cartesian positioning system and the speed of the screw of the print head.

Beside the normal function of the CNC-controller, some advanced functionality has been applied to maintain and monitor the quality of the produced object. In order to do it right from the first time a module for the monitoring of the shape of the extruded material, based on a laser-line and camera system (fig.5), is implemented. The module will control the dimensions (height, width) of the extruded material and will influence extrusion speed to maintain constant dimensions of the laid down material. Interruption of the deposited material will be registered and if necessary corrected. When the product is finished, a certificate with logged data can be provided with the product.

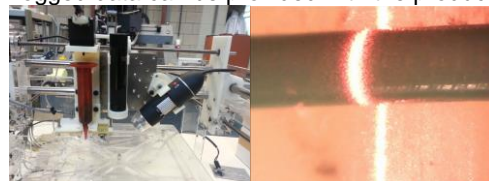


Fig. 5. Camera and laser line system for the control of the extruded material

4. Results

The main objective of the research is the development of a screw extruder based 3D printer capable of printing a broad range of thermoplastic polymer materials. To prove the functionality of the extruder tests were done with four different materials: polypropylene (PP) as a semi-crystalline thermoplastic and polystyrene (PS) representative of the group of amorphous thermoplastics. The other two materials are the biodegradable thermoplastics polycaprolactone (PCL) and polylactide acide (PLA), based on renewable resources. Each of these materials has a different Melt Flow Index (MFI), starting from 1gram/10min for PLA up to 12 gram/10min for PS. The temperature for the extruder was adapted for each material according to the softening and melting temperature of the polymer.

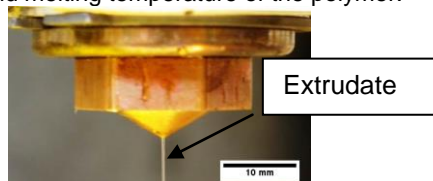


Fig. 5. Extruded thermoplastic material (PCL)

A nozzle with extrusion diameter of 0,2mm was used in these tests, comparable to nozzles in commercial available FDM-systems in the range between 0,33mm and 0,13mm. The result is an extrudate with a smooth surface and without trapped air, as shown in figure 5 for the PCL material. Comparable results were found for the other materials.

5. Conclusions and future works

A novel screw extrusion based 3D printing process is presented, starting from an overview of the different solutions to process thermoplastic polymers. With conclusion, that nevertheless the complex design of the screw extrusion based process, this a good solution is for the existing limitations and drawbacks, as there are the limited range of materials, filament extrusion, material degradation, trapped air and discontinuous process. The working of the screw extrusion based system is proved, by the processing of PLA, PP and PS in arrange of melt flow index between 1 and 12 gram/10min.

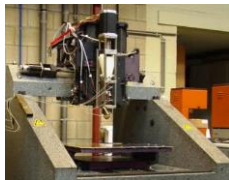


Fig. 6. Screw extrusion based AM-system

The screw extruder system is mounted on an XYZ positioning system (fig.6), controlled by a CNC controller based on the open architecture principle. This approach is used to have full access to the parameters of the process and to have the ability to expand the system with advanced functionality to improve process

quality and reduce scrap. Therefore a camera laser line system is implemented to monitor the dimensions (height and width) of the extruded material.

Still some work has to be done in improving the process. The nozzle diameter will be changed to 0,1mm resulting in changing and optimising the process parameters as there are temperature, speed of extrusion and connection between the positioning velocity and extrusion speed.

Acknowledgements

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