

## Screw Extrusion Based 3D Printing, a Novel Additive Manufacturing Technology

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### Abstract

Extrusion based 3D printing is a popular additive manufacturing process for the production of plastic prototypes and single or small series of functional products. The most common known extrusion based technique is Fused Deposition Modeling™, based on filament deposition. Although this is a popular 3D printing technique, there are some disadvantages which impose some limitations for the end users. Primarily the limited range of commercially available materials, secondly the feed material needs to be a filament, with a narrow tolerance with respect to the nozzle diameter, in order to prevent blocking of the nozzle. Especially the limited range of materials discourages a lot of end users to produce parts by means of filament extrusion 3D printing. This resulted in the development of alternative extrusion based additive manufacturing processes. A good processing technique was found in the conventional plastic extrusion process in which granulate is fed into a plastic processing screw. The paper compares three extrusion based processes (filament, syringe and screw extrusion), resulting in the choice for the screw extrusion based process. A concept for this process has been worked out and a functional screw extrusion based 3D printing process has been developed that complies with the objectives.

### Keywords

Additive Manufacturing, Extrusion Based 3D Printing

## 1 INTRODUCTION

Additive manufacturing (AM), also called 3D printing, is a generic name for a group of novel production processes that joins materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies [1].

The AM process starts from a digital surface model of an object; this can be generated from a CAD software or scan data. Next process specific software will process this data; cross-sections are determined by dividing the model into layers depending on the layer resolution of the process. Each of these cross-sections will be hatched with a certain pattern as infill structure for the object. The construction starts by sending the patterns to the selected additive system, which will build the object by joining the material layer upon layer. Afterwards a finishing step is mostly applied to remove support structure and smooth the layered texture of the surface.

The first AM-processes were limited to the quick production of prototypes, so called rapid prototyping, due to the limited mechanical properties of the objects [2]. Thanks to the increasing interest and technological evolution, these production processes evolved and are nowadays used for the production of single or small series of objects with functional aspects and high added value.

3D printing is a subgroup of these processes fabricating objects through the deposition of a material using a print head, nozzle or another printing technology [1]. This paper will present the preliminary research and development of a screw extrusion based 3D printing process to overcome the limitations of the filament based extrusion process.

Filament based extrusion, as shown in figure 1, is a popular process for the creation of functional products. 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/ram to extrude the material through the nozzle [4]. This extruded polymer is deposited according to the pattern generated from the 3D model on the build platform or previous layer. After the layer is finished the building platform is lowered a layer thickness and a new layer can be created.

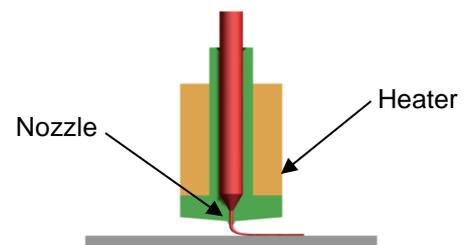


Figure 1 - Filament based 3D printing

Extrusion using the filament based extrusion 3D printing technique requires the material to be processed in a filament form. This filament is produced with a conventional polymer extrusion process, but in comparison to conventional production, this filament will be extruded to a very tight diametric tolerance which can't be achieved by conventional extruders [5, 6]. Since the filament based 3D printing machine drive pushes the filament feedstock through the liquefier, a variation in diameter may cause blocking. Further drawbacks of this process are buckling [4, 7, 8] and slippage of the wire on the pinch wheel [7], causing an interruption of the building process and requiring an interaction of the operator [3, 5, 6].

Besides these process drawbacks, also a limitation of available polymer materials is a shortcoming of the filament based 3D printing process. Commonly objects are 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]. A material called Ultem 9085 can be processed, with applications for aerospace and marine industry [9, 10]. Besides these materials, some small producers can deliver machines able to process polylactic acid (PLA), a bio-degradable polymer. Very little effort has been made to develop or adapt the filament extrusion to process a broad range of thermoplastic materials. [11]

Some research has been done in the field of screw extrusion based 3D printing systems. Research was mostly done to avoid the extrusion of a filament of new designed or existing materials as feedstock for the 3D printing process. Most of this research was applied in the area of bioengineering, thanks to the small amount of polymer required for the production of an object in comparison to other AM-processes. Another field of application is 3D printing of ceramics.

In 2005 A. Bellini reported a mini screw deposition (MED) 3D printing system for the processing of ceramic materials [11]. A mini extruder with a constant inner diameter was applied, as can be concluded from their presented work [11, 12]. The same hardware was used for the fabrication of polycaprolactone (PCL) scaffolds, whether or not blended with hydroxyapatite [13, 14, 15]. The major drawback of this system is the trapped air in the polymer, causing interruptions in the extrusion process.

Also the School of Engineering, Auckland University of Technology in cooperation with National University of Singapore reported the implementation [16, 17] of the Screw Extrusion System (SES), mounted on a positioning system. They are studying the ability of curved layer fused deposition modelling. The shown processing screw also has a

constant inner diameter [16], with the same limitations as the one presented by A. Bellini.

The department of applied engineering sciences of the university college of Ghent published their findings of the new developed COMET-system [18]. This system, designed to reduce the thermal degradation of biodegradable thermoplastics during processing [19, 20], consists of a plunger pushing the material through a heated torpedo, to melt the material, in a designed screw that transports the material to the nozzle. Also other thermal sensitive thermoplastics can be processed with the system.

## 2 EXTRUSION BASED PROCESSES.

Filament extrusion based 3D printing has several drawbacks as described in the previous paragraph. For these reasons new processes as syringe based extrusion and screw extrusion are investigated to overcome those problems.

### 2.1 Syringe based extrusion

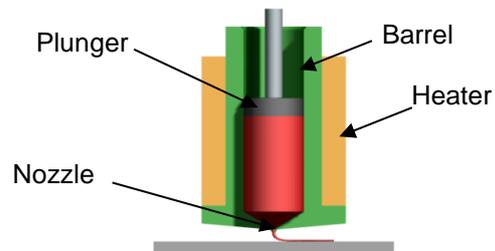


Figure 3 - Syringe based 3D printing

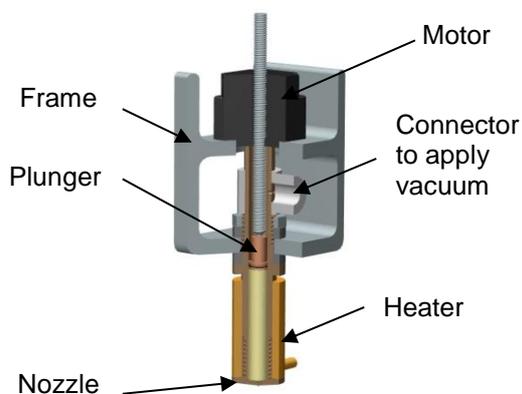
An alternative way to create an extrusion based AM-system is based on the syringe principle. This method is generally used for materials that use a chemical reaction to cause solidification [3]. A reservoir is filled with the designated material and heated or cooled to processing temperature. A controlled plunger will push the material out of the reservoir.

For the processing of thermoplastic polymers a proof of concept was worked out at KU Leuven, Campus De Nayer by creating a syringe tailored for polycaprolactone (PCL) (Perstorp Capa™ 6506) (Figure 3, 4). The components of this process, barrel, nozzle and plunger, need to withstand an elevated temperature depending on the processed material and must be suitable to transfer the applied heat to melt the polymer.

A heater is mounted around the barrel to heat up the polymer. A homogeneous temperature around the barrel surface was created with the application of highly thermal conductive copper, also the nozzle is constructed from the same material to prevent blocking of the small extrusion diameter. Besides the material selection also the tolerance between barrel and plunger need to be considered. To prevent leakage between these components a narrow tolerance is required. Furthermore a frame is

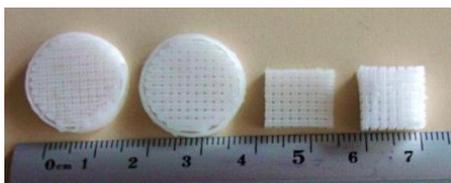
constructed around the syringe to mount a stepper motor to control the position of the plunger.

To start the 3D printing process a certain amount of material is placed inside the barrel. Then, the heater will heat up the polymer in the barrel. The remaining air inside the barrel is evacuated by a vacuum pump connected to a coupling on the side of the barrel. On the same spot as the coupling, holes are made in the barrel to evacuate the air. The vacuum is applied for several minutes and then the barrel is closed by moving the plunger over the holes. The deposition of the material is controlled by pushing down the plunger. The extruded material is laid down according to the predetermined pattern generated by the controlling software, creating the object.



**Figure 4** - Tailored syringe and frame.

Scaffold test objects (figure 5) were printed with a nozzle diameter of 0,5 mm to test the processing parameters and capabilities of the system.



**Figure 5** - Syringe based extrusion test objects

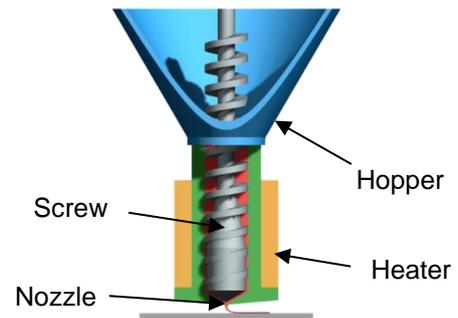
Nevertheless the satisfying results of this proof of concept, some important disadvantages were found.

- After a long printing time the material in the syringe will undergo thermal degradation, resulting in poor material properties.
- Also differences in melt viscosity were noticed during processing caused by an inhomogeneous temperature distribution inside the barrel.
- Furthermore, during the production of large objects, the syringe needs to be refilled repetitively causing an interruption in the building process, cooling down of the product and syringe, resulting in a poor adhesion between the influenced layers [21].

As indicated by the disadvantages of this process, it is not been considered as applicable for the production of functional objects.

## 2.2 Screw based extrusion

In an attempt to provide a solution to the problems mentioned a screw based extrusion process is studied (figure 6), as is commonly used in the plastic processing industry to create continuous fixed shaped profiles. Especially a three section screw is desired to create a stable process and homogeneous melt.



**Figure 6** - Screw based extrusion process

Polymer granules are fed into the hopper and transported to the nozzle by the screw. Heat is applied to soften and finally melt the polymer granules into a viscoelastic melt. The pressure is built up by the geometry of the screw to overcome the backpressure from the nozzle, acting as a die for the extrusion process, to achieve extrusion and finally the material deposition.

A number of benefits speak for this extrusion based 3D printing system:

- Granules can be fed directly into the barrel, avoiding that granules first need to be processed into a filament by a similar extrusion process.
- By using granules as feedstock, a continuous process is realized.
- A broad range of polymer materials can be processed in a wide range of viscosities, increasing the application area of 3D printed objects.
- Less thermal degradation of the polymer due to the homogeneous melt process and the small amount of melted polymer.

A setback for the implementation of a screw extruder system is the design and construction of a three section screw. This type of screw is required to avoid trapped air in the polymer melt, preventing interruption of extrusion [7, 8, 11].

## 3 SCREW EXTRUDER CONCEPT

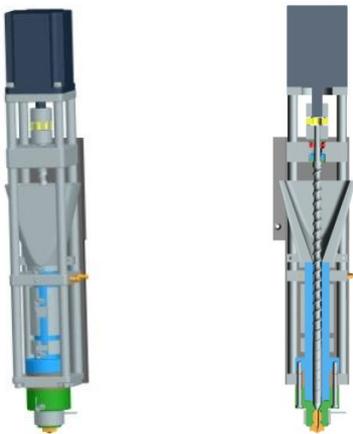
### 3.1 Screw extruder

The design strategy of this extruder is comparable to the design of a conventional plastic extrusion process. The first step in the design is the selection

of the materials to be processed, in this case different types of thermoplastic polymer materials are requested. Plastics from the two subcategories of thermoplastic polymers were selected: polystyrene (PS) as representing the amorphous plastics and polypropylene (PP) representing the semi-crystalline plastics. Furthermore, the application of bio degradable materials needs to be considered, e.g. polycaprolactone (PCL) and polylactic acid (PLA). Due to the fact that different materials are used, as described above, the design of the screw can't be optimised for a single type of material. An all-rounder design has to be developed to be able to process the broad range of materials.

Besides the material, the nozzle diameter and the processing speed will determine the dimensions of the extruder. These parameters will constrain the backpressure of the nozzle. This pressure will determine the geometry of the extruder, which needs to build-up a pressure to overcome the backpressure of the nozzle.

Starting from the design of the nozzle geometry, the screw will be designed. In addition the barrel is determined by the existing pressure as well. Besides these three important parts of the extruder, a frame to attach the extruder to the machine and a motor to drive the screw are needed. These assembled components will create the extruder as shown in figure 6.



**Figure 6 - Design of the screw extruder unit**

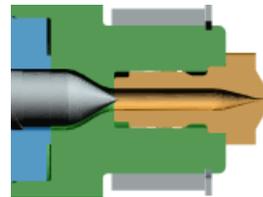
### 3.1.1 Nozzle

In comparison with conventional extrusion processes, the printing nozzle should be seen as the die creating the required shape. For extrusion based 3D printing this die will commonly have a round section. The diameter of this nozzle should be as small as possible, due to the fact that this diameter will determine the smallest printable feature. On the other hand this diameter will determine the backpressure of the system: the smaller the diameter the higher the pressure. Moreover, die swell depends on the shape and backpressure of the nozzle. For this design nozzle diameters from 0,5 mm to 0,2 mm were selected.

With the simulation software Virtual Extrusion Laboratory (VEL), different geometries were simulated. The result is a smooth profile (figure 7) with a gradual restriction of the diameter and a low inclination.

To minimise the die swell (diameter increase of the extrudate when the plastic leaves the nozzle), the nozzle is equipped with a small shaft with continuous diameter in the nozzle to create a section for the relaxation of the plastic. Also an extra heater is mounted to the nozzle of the extruder to heat the nozzle improving the relaxation and preventing blocking of the system.

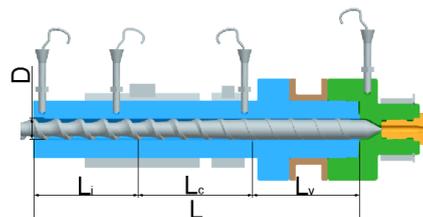
The nozzle as shown in figure 7 is divided in two parts, one fixed to the barrel with the supplementary heater attached to it and a second exchangeable part in highly thermal conductive copper with the extrusion channel in it. In this way quick changes can be made between different extrusion geometries.



**Figure 7 - Nozzle**

### 3.1.2 Screw and barrel

A conventional extrusion screw is shown in figure 8 and contains 3 sections: the feed section ( $L_i$ ), the melting section ( $L_c$ ) and the metering section ( $L_v$ ). At the feed section material is fed from the hopper into the extrusion process. The granules are preheated by use of an external heater, until they are softened. Next the softened granules enter the melting section, where the plastic is equally melted to a viscoelastic liquid. The melting is stimulated by internal friction between the molecules of the polymer caused by the compression of the plastic granules. A second advantage of the compression is the evacuation of the entrapped air in the melt. This compression section will also generate the required pressure to overcome the backpressure of the nozzle. Before entering the nozzle the viscoelastic melt will pass through the metering section to create a homogeneous melt, both in composition and temperature. The lengths of the three sections are related to the processed material.



**Figure 8 - Extrusion screw and barrel**

The calculation of a screw can be found in standard polymer processing handbooks [22], but also a lot of work has been done by simulation software, e.g. VEL. The most important parameters characterizing the screw are:

1. Diameter of the screw (D)
2. L/D-ratio: often used to determine the relative length of the screw.
3. Compression ratio (CR): the ratio between the depth of the feed section and the depth of the metering section.

A L/D-ratio of 10 was selected to minimise the amount of material in the extruder resulting in a reduction of the amount of time that the plastic would stay at elevated temperature.

The CR is used to give an idea of the screw compression. This ratio should be high enough to compress the low bulk density of the unmolten plastic granules into a viscoelastic liquid without air-bubbles and generates the required pressure to overcome backpressure of the nozzle.

Last, the clearance between the screw and barrel needs some attention. If this gap is too large the productivity of the extruder will decrease due to the back flow of the melt. The barrel surrounding the screw also needs to withstand the pressure that is built up in the system.

### 3.1.3 Peripherals

To assist the melting process two ceramic band heaters are mounted around the barrel to heat up the system. During the start-up of the system, these heaters together with the nozzle heater will melt the present polymer. After the start up and during production, the heaters will guard the temperature preventing the system from being blocked. These heaters are controlled by use of five thermocouples, equally spaced on the barrel. The temperature control-loop is integrated on the same system that is used for the motion control.

To drive the extrusion screw a stepper motor is connected to this screw. The specifications of the motor are depending on the existing torque caused by pushing the polymer forward during processing. This motor is proportionally controlled in function of the speed of the positioning system.

## 4 RESULTS

The main objective of the development of the screw extruder for 3D printing is the processing of a broad range of thermoplastic polymer materials. Therefore, the initial tests to prove the functionality of the extruder were carried out with the three materials: PP, PS and PCL as mentioned above. The selected materials have a melt flow index (MFI) between 1 gram/10min (PCL) and 12 gram/10min (PS). The temperature for the extruder was adapted for each material according to the melting or softening temperature of the polymer.

A nozzle with extrusion diameter of 0,20mm was selected for these tests.

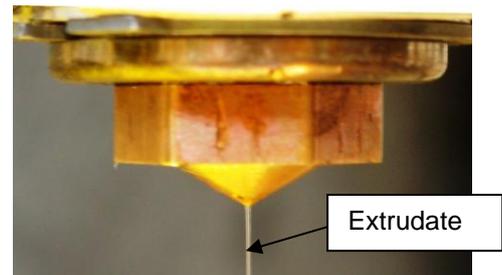


Figure 9 - Extruded PCL

As shown in figure 9 a fine PCL filament was extruded, with a smooth surface and without trapped air. Also the die swell is negligible. For both other materials PS and PP comparable results were found.

## 5 CONCLUSIONS

A novel screw extrusion based 3D printing process was presented. Starting from a preliminary research of extrusion based processes, a concept for a screw extruder system was realised. A solution was given to the existing limitations and drawbacks, as there are the limited range of materials, extra step of filament extrusion, material degradation, trapped air and a discontinuous working principle.

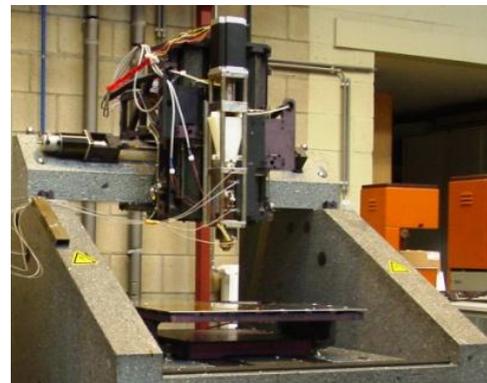


Figure 10 - Screw extrusion based AM-system

From the concept a design is worked out, based on the conventional screw extrusion process, fulfilling the requirements of processing a broad range of materials without the need of creating a filament.

The design of the screw extruder is realised and implemented on an own build XYZ printing system (figure 10). First tests, with three different polymer materials (PS, PP and PCL) have proven that the screw extruder fulfils all functional requirements.

Nevertheless the satisfying results, there is still some room for improvements, e.g. optimising process settings (temperature, extrusion speed).

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