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USE OF 3D PRINTING TECHNOLOGY FOR PROTOTYPING IN MECHANICAL ENGINEERING

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Abstract: *The article presents a brief history of the processes of additive production (3D printing), describing and classifying them. At the same time, two prototypes are presented in the material, a vertical axis wind turbine and the body of a piston of a fertigation pump that were successfully produced at IHP with the help of this technology.*

Keywords*: Additive manufacturing, 3D printing, FDM, vapor smoothing, FFF.*

1. Introduction

The 3D printing process builds a three-dimensional object from a computer-aided design (3D CAD) model, usually by successively adding material layer by layer, which is why it is also called additive manufacturing, unlike conventional machining, casting and forging processes, where material is removed from a stock item (subtractive manufacturing) or poured into a mold and shaped by means of dies, presses and hammers.

2. Brief history of 3D printing

David E.H. Jones was the first who laid out the concept of 3D printing in the journal "New Scientist", in 1974. [1]
In 1981, Hideo Kodama of Nagoya Municipal Industrial Research Institute invented two additive methods for fabricating three-dimensional plastic models with photo-hardening thermoset polymer, where the UV exposure area is controlled by a mask pattern or a scanning fiber transmitter.[1] On 16 July 1984, Alain Le Méhauté, Olivier de Witte, and Jean Claude André filed their patent for the stereolithography process. Three weeks later in 1984, Chuck Hull of 3D Systems Corporation filed his own patent for a stereolithography fabrication system, in which layers are added by curing photopolymers with ultraviolet light lasers. Hull defined the process as a "system for generating three-dimensional objects by creating a cross-sectional pattern of the object to be formed". Hull's contribution was the STL (Stereolithography) file format and the digital slicing and infill strategies common to many processes today. [1]
The technology used by most 3D printers to date—especially hobbyist and consumer-oriented models—is fused deposition modeling, a special application of plastic extrusion, developed in 1988 by S. Scott Crump and commercialized by his company Stratasys, which marketed its first FDM machine in 1992.[1] By the mid-1990s, new techniques for material deposition were developed at Stanford and Carnegie Mellon University, including microcasting and sprayed materials. Sacrificial and support materials had also become more common, enabling new objects geometries.[1]
The term 3D printing originally referred to a powder bed process employing standard and custom inkjet print heads, developed at MIT by Emanuel Sachs in 1993 and commercialized by Soligen Technologies, Extrude Hone Corporation, and Z Corporation. The year 1993 also saw the start of a company called Solidscape, introducing a high-precision polymer jet fabrication system with soluble support structures. [1]
In 1995 the Fraunhofer Institute developed the selective laser melting process. Fused Deposition Modeling (FDM) printing process patents expired in 2009. As the various additive processes matured, it became clear that soon metal removal would no longer be the only

metalworking process done through a tool or head moving through a 3D work envelope transforming a mass of raw material into a desired shape layer by layer.
In 2008 Shapeways, a 3D printing service is launched in the Netherlands. A bit like RepRap, Shapeways makes 3D printing available to a wider audience. Rather than giving people their own 3D printers, however, Shapeways lets users submit their own 3D files, which the company then 3D prints and ships back. Shapeways rapidly expands to a factory in Queens, New York, and raises substantial venture funding. It also becomes a marketplace for 3D printed objects, which the company will then print on demand. Shapeways makes 3D printing accessible to a non-tech crowd, including artists, architects and other creative individuals. [2]
The 2010s were the first decade in which metal end use parts such as engine brackets and large nuts would be grown (either before or instead of machining) in job production rather than obligated being machined from bar stock or plate. As technology matured, several authors had begun to speculate that 3D printing could aid in sustainable development in the developing world.
In 2012 Filabot develops a system for closing the loop with plastic and allows for any FDM or FFF 3D printer to be able to print with a wider range of plastics. 2014: Georgia Institute of Technology Dr. Benjamin S. Cook and Dr. Manos M. Tentzeris demonstrate the first multi-material, vertically integrated printed electronics additive manufacturing platform (VIPRE) which enabled 3D printing of functional electronics operating up to 40 GHz.

3. Technologies in 3D Printing [3]

- Stereolithography (SLA) – This 3D printing method is the first method in the history of 3D printing. It is the oldest but is still being used today. Most printing techniques use a CAD file to process the object, which is then converted to a format that a printing machine can understand. In this technology, a software processes the CAD model and generates the STL file that contains the information for each layer. The whole process includes a consequent printing layer by layer. There could be up to ten layers per each millimeter. Once all layers are printed, the object needs to be rinsed with a solvent and placed in an ultraviolet oven to finish the process.
- Digital Light Processing (DLP) is similar to stereolithography. Larry Hornbeck of Texas Instruments created this technology in 1987. This is popular in the production of projectors and is applicable for cell phones and 3D printing as well. DLP technology uses digital micromirrors laid out on a semiconductor chip. Although DLP and SLA both work with photopolymers, they use different sources of light. DLP uses more conventional sources like arc lamps. Moreover, DLP uses a liquid crystal display panel that is being applied to the whole surface of the building material. The material for printing is a liquid plastic resin placed in the transparent resin container. The resin quickly hardens when exposed to a large amount of light. The printing speed is fast. Compared to SL, DLP produces more robust 3D objects with excellent resolution. It also uses lesser material that results in lower cost and reduced waste.
- Fused deposition modeling (FDM) is the most popular technology in 3D printing. It allows you to print concept models and final end-use products with engineering-grade thermoplastic. FDM is the only 3D printing technology that builds parts with production-grade thermoplastics that produces excellent mechanical, thermal and chemical qualities making it very useful and appealing to manufacturers and engineers. FDM Technology builds a 3D object layer by layer from the bottom to the top by heating and extruding thermoplastic filament. The whole process is similar to stereo lithography but slower. This technology uses a special software to cut the CAD model into layers and calculate the way the printer extruder will build each layer. The printer will heat the thermoplastic up to its melting point and extrudes throughout the nozzle onto the base to build platform along the calculated path. A computer will translate the dimension of the object into X, Y and Z coordinates and controls the nozzle and the base, so that it follows the calculated path during printing. This technology is used in automobile companies like Hyundai and BMW and food

companies including Nestle and Dial. FDM technology is simple to use, and it can build complex geometries and cavities. Moreover, it is environment-friendly.

- Selective Laser Sintering (SLS) This technology uses a laser as a power source to form 3D objects. Carl Deckard, a student of Texas University and his professor Joe Beaman discovered this technology in 1980. SLS has some resemblance with SLA but they differ in the material used. SLS uses powdered material instead of liquid resin. In addition, SLS does not use any support structures because the object being printed is already surrounded by unsintered powder. Similar to other technologies, SLS starts with the creation of the CAD file, which is then converted into a .stl format using special software. This technology allows nylon, ceramics, glass and metals like aluminum, steel or silver. Due to its wide variety of materials, SLS is popular for customizing 3D objects.
- Selective laser melting (SLM) This technique also uses CAD data and builds a 3D object through a high-power laser beam that fuses and melts metallic powders. Several sources consider SLM as a subcategory of SLS but the two technologies have major differences. The SLM processes fully melt the metal into solid 3D parts, unlike selective laser sintering. SLM also uses a CAD file, and special software to slice the CAD file into 2D layers. When the file is loaded, the printing machine's software will assign parameters and values for construction of the path. The fine metal powder is evenly distributed onto the plate and a high laser energy will be directed into it to fuse each slice of 2D layer image. The energy is so strong that the metal powder melts and forms a solid object. The process repeats for the next layer until the product is complete. SLM uses the following metals: stainless steel, titanium, cobalt chrome, and aluminum. SLM is widely used in objects with complex geometries and structures with thin walls and hidden voids or channels. This technology is used in aerospace manufacturing and orthopedics but it is not widely distributed among households.
- Electronic Beam Melting (EBM) This technology is another type of additive manufacturing for metal parts. It is similar to SLM as it also uses a powder bed fusion technique. However, instead of using a high-power laser beam as its power source, it uses an electron beam. This is the main difference between the two; the rest of the process is the same. EBM is slow and expensive compared to SLM. Also, the materials are limited. Most materials used are commercially pure titanium, Inconel 718 and Inconel 625. This technology focuses on medical implants and aerospace area.
- Laminated Object Manufacturing (LOM) Helisys Inc., a California-based company, develops this rapid prototyping system. During LOM process layers of adhesive-coated paper, plastic or metal laminates are fused together through heat and pressure. Then, they are cut into shapes with computer-controlled laser or knife. The post-processing of 3D printed parts includes machining and drilling. This technology also starts with a CAD file that is later converted into an STL or 3DS format. LOM printers use continuous sheet coated with adhesive and laid down cross substrate with a heated roller. The heated roller is passed over the material sheets on substrate melts the adhesive and the laser or knife will then trace it to its desired dimension. When the layer is finished, it will move down and a new sheet will be processed. The process is repeated until the 3D object is fully printed. LOM is not that popular but it is one of the most affordable and fastest 3D printing technology. Moreover, printing is low cost because it does not use expensive materials.
- Binder Jetting (BJ) Technology. The Massachusetts Institute of Technology invented BJ 3D printing. This is called by many other names such as: Powder bed printing, Inkjet 3D printing, Drop-on-powder, Binder Jetting (BJ) – the most popular name. BJ uses two types of materials a powder-based material and a bonding agent. The "bonding" agent acts as a strong adhesive that holds the powder layers together. The printer nozzles extrude the binder in a liquid form similar to a regular 2D inkjet printer. After completing each layer, the build plate lowers slightly to allow for the next one. The process is repeated until the process is finished. This 3D printing technology doesn't give you high-resolution or overly rugged 3D objects. But it allows you to print parts in full color. BJ is

being used in aerospace, automotive and medical industries. Material Jetting (MJ) Polyjet and Wax Casting Technology Material Jetting is also called wax casting. Unlike the other 3D printing technologies no one invented MJ. This is considered more of a technique than an actual printing process. Jewelers have used this for centuries to produce high-quality customizable jewelry. MJ starts with a 3D model (CAD file). Once this is uploaded to the printer, the system does all the rest. The printer adds molted (heated) wax to the aluminum build platform in controlled layers. It will be sweep evenly across the build area. As soon as it lands on the build plate, it begins to cool down and solidify (UV light helps to cure the layers). As the 3D parts build-up, a gel-like material helps support it. Once it's done, you can easily remove the object by hand or by using powerful water jets. Once the part is complete, it can be used right away. No need for further post-curing.
This produce objects with good resolution. Polyjet MJ 3D printers are used mainly in the dental and jewelry industries.

4. Prototypes made at IHP with the help of 3D printing technology

This chapter presents two of the prototypes produced at the Research Institute for Hydraulics and Pneumatics INOE200-IHP.
The prototyping process of vertical axis wind turbines (1:5 scale). [4]
Figure 1 shows the 3D model of the wind turbine, realized in the CAD modeling software SOLIDWORKS.

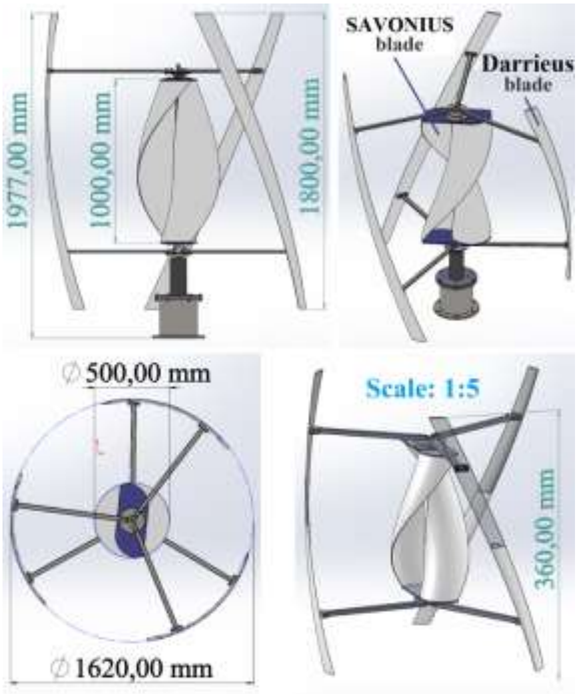

Fig. 1. 3D CAD models from the SolidWorks software

Printing was done on the BCN3D SIGMA R19 Printer (FFF) with the following facilities:
•Architecture: Independent Dual Extruder (IDEX);
•Printing volume: 210 mm x 297 mm x 210 mm;
•Heated bed maximum temperature: 100 °C;
•Positioning resolution (X/Y/Z): 1.25µm/ 1.25µm/ 1µm;
•Firmware: BCN3D Sigma - Marlin;
•Extruder system Extruder Bondtech ™ high-tech dual drive gears; Hotends: Optimized and manufactured by e3D ™;
•File preparation software: BCN3D Cura.
Both the printer and the slicing software of the 3D models are shown in figure 2.

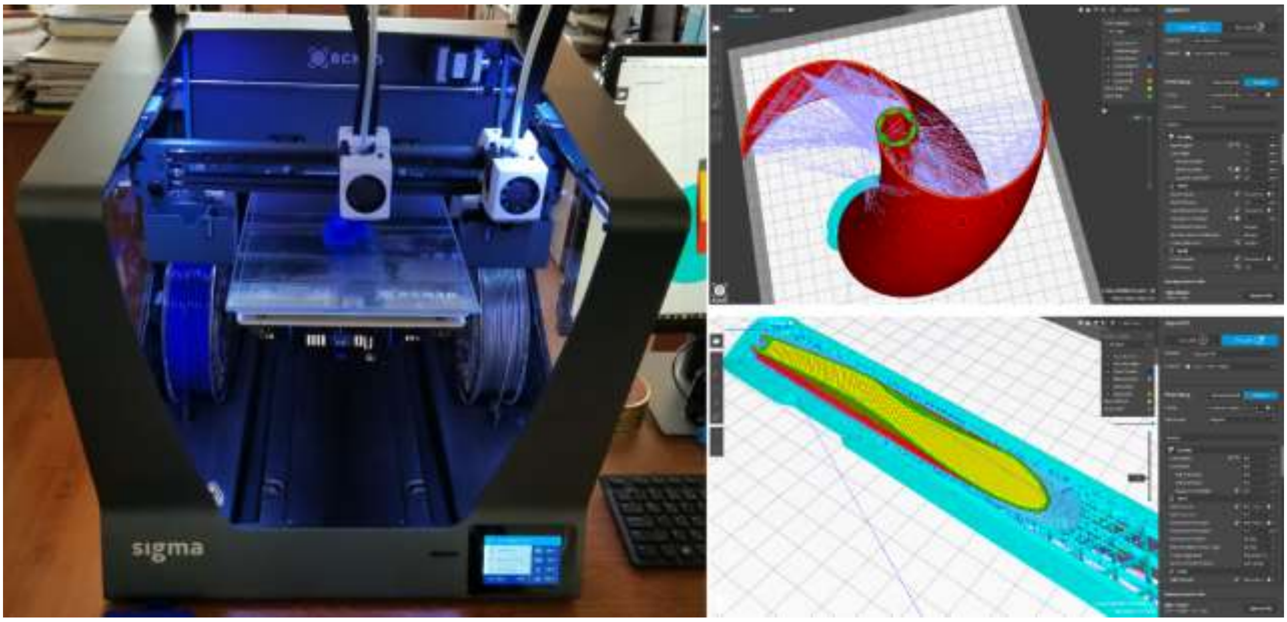

Fig. 2. SIGMA R19 Printer and BCN3D Cura software

All the parts of the functional model were printed with PLA and for the parts that needed support PVA was used, which dissolves easily in water.
Parameters of the 3D printing process: the filament diameter was 2.85 mm, 0.4 mm hotend diameter, 0.2 mm layer height, 35% or 100% infill density, 205°C printing temperature, 60°C build plate temperature and a conservative print speed of 50 mm/s.
Because the blades of the Darrieus turbine are larger than the printer can produce, they were divided into two pieces, and due to their curvature, in two planes, it was necessary to print with support material. Figure 3 shows the parts that needed support material, including the arms for the purpose of supporting the Darrieus turbine; they have practiced 2 through-holes that are necessary for the assembly with screws.

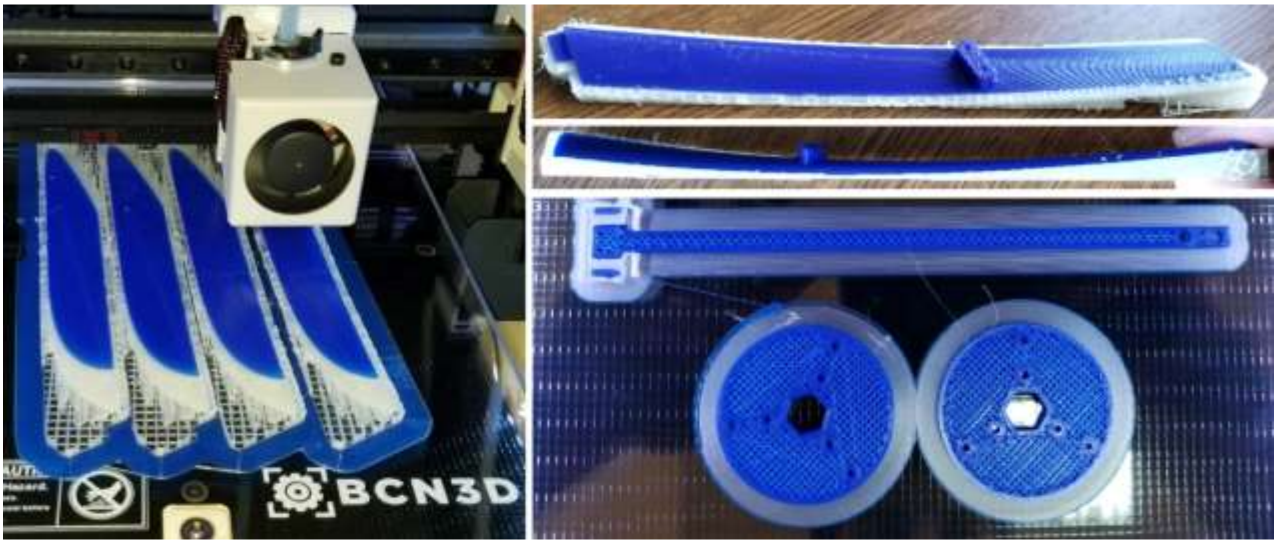

Fig. 3. The printed parts that needed support material.

Figure 4 shows the parts that did not need support material during the printing process; they are: the covers of the Savonius turbine, which have practiced a channel that rigidifies the whole sub-assembly, the Savonius turbine itself, as well as the bearing base, which has the role of support for hexagonal shaft and turbine.

Fig. 4. Components that did not need support material during the printing process.

And in Figure 5 is presented the prototype of the wind turbine with vertical axis, on a small scale.

Fig. 5. The prototype of vertical axis wind turbines (1:5 scale)

The prototyping process of the injection device piston used for fertigation. [5]
This section presents the 3D printing process of the piston and the process of improving surface quality. Figure 6 shows the 3D model made in the SolidWorks modeling software, as well as a section of it.

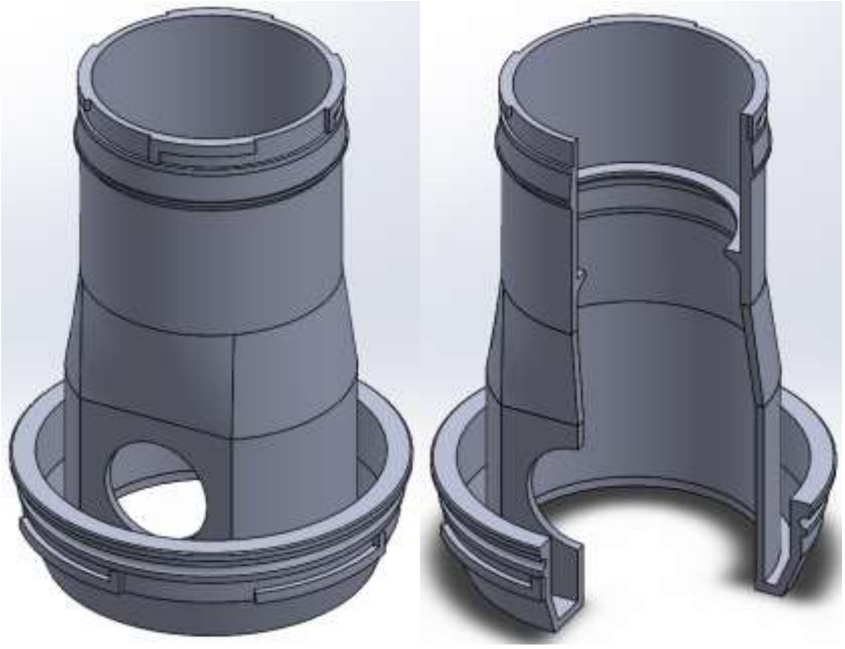

Fig. 6. 3D CAD models from the SolidWorks software

The piston body was made of ABS filament and the support structure was intended to support the layers with an angle greater than 45°.
Parameters of the 3D printing process: the filament diameter was 2.85 mm, 0.4 mm hotend diameter, 0.2 mm layer height, 99% infill density, 250 °C printing temperature, 95 °C build plate temperature and a conservative print speed of 55 mm/s.
The 3D model was converted to STL format and was imported into the Cura slicer (Figure 7) where the printing parameters were set.

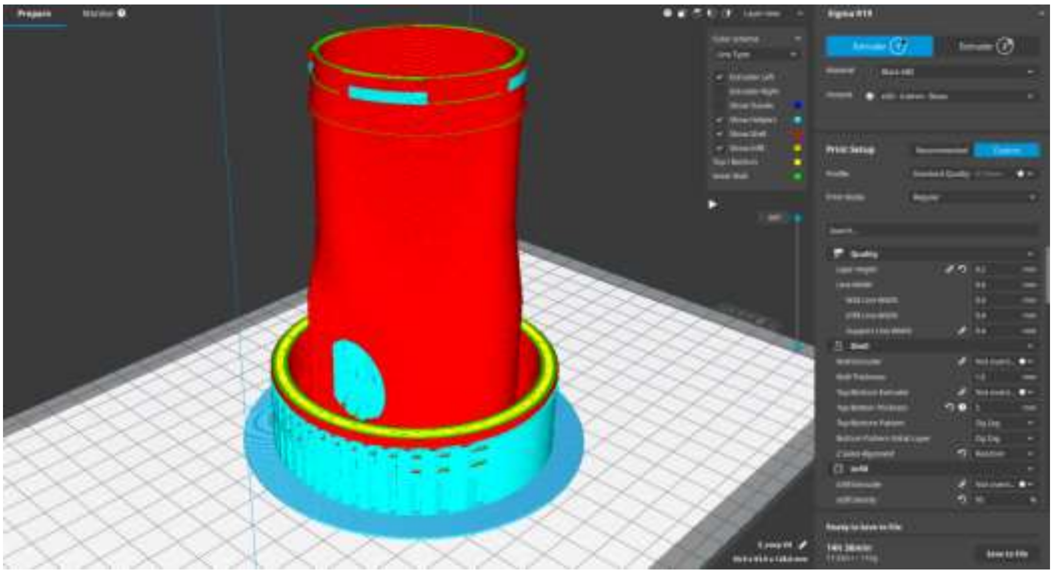

Fig. 7. The 3D model of the piston from the Cura slicer

The piston resulted at the end of printing can be seen in figure 8, as well as the fact that a closed enclosure was used during printing to prevent the deformation of the part and the delamination of the layers.

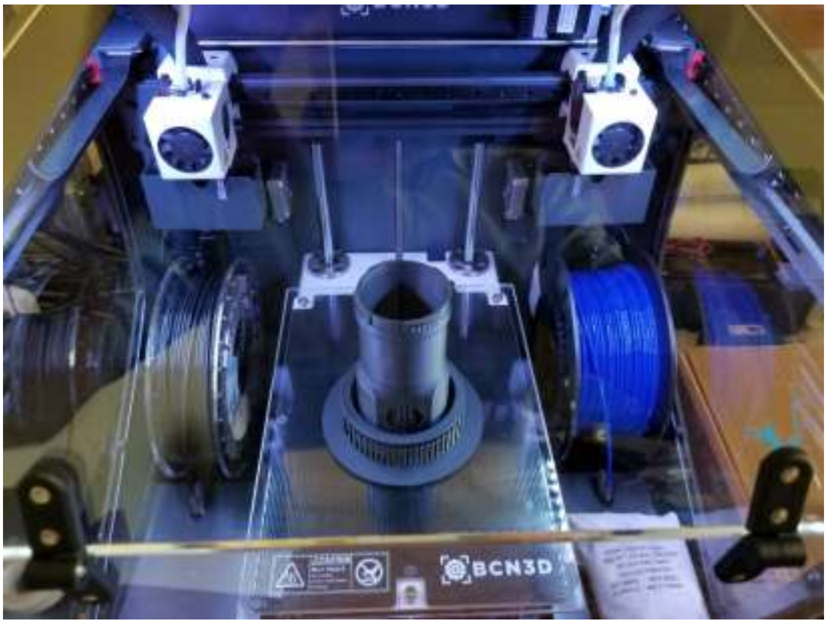

Fig. 8. 3D printer and piston body at the end of the printing process

Due to the fact that the fertigation pump operates at a maximum pressure of 6 bar and for a smoother flow of the liquid through the pump body, the piston has been applied the "vapor smoothing" process (figure 9). This process consists in the superficial melting of the surface of the ABS part with the help of an acetone vapor bath. The piston was placed in a tightly sealed vessel that has a sieve high up against the bottom of the vessel on which the piece sits. On the bottom of the vessel there is acetone and a piece of metal embedded in the glass that is driven by a device that heats the vessel and at the same time rotates the metal piece. Stirring the acetone as well as increasing the temperature increases the rate of acetone evaporation and finally the duration of the entire process.

Fig. 9. Vapor smoothing process installation

After about 15 minutes, the piece was removed from the vessel and left for the molten acetone surface to harden. The final quality of the surface can be seen in figure 10.

Fig. 10. Surface quality after vapor smoothing process

5. Conclusions

With the help of rapid prototyping technology, both the wind turbine and the piston body of the irrigation pump were produced quickly and cheaply.

Due to the additive nature of this technology, complex parts that could not be made with classical processes (milling, turning, casting ...), can easily be achieved.

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