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"In the test conducted, the parts showed good shape reproducibility, without structural defects and with a degree of densification in line with expectations. It is therefore considered a technology with potential for application in the technical ceramics segment.»

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FDM additive manufacturing of ceramic parts: testing PAM technology

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Introduction

Additive Manufacturing (AM) is a method of producing parts that consists of adding material layer by layer, through a specific equipment, forming a precise geometric shape [1]. This process is commonly referred to as 3D printing [2].

The main advantages of additive manufacturing over conventional techniques are the possibility of producing parts with complex geometry with high precision, no need to use tools, flexibility in terms of design and reduced consumption of raw materials. It also has the advantage of producing small batches of parts, with relatively low costs [1, 3].

There are several AM technologies on the market and the main differences lie in the way each layer is constructed and the way the layers are connected to each other. These two parameters are important as they will determine the finishing precision of the final product as well as its mechanical properties [2].

Unlike polymeric materials and metals, additive manufacturing of ceramic materials is still in its infancy. The processing of ceramic materials using additive manufacturing still has major limitations at the technology level due to the high melting points of these materials, the need to perform a subsequent heat treatment to obtain the desired structural properties (sintering), the brittle nature of ceramic materials and due to the fact that they have low ductility (when compared to metals or plastics).

However, there is a growing interest in this type of technology for producing ceramic materials, not only traditional ceramics, but also technical ceramics due to the fact that they are materials that have high hardness, abrasion resistance and mechanical strength, as well as high resistance to oxidation and corrosion, when compared to metals, and can be good insulators both thermally and electrically.

This article presents a test of the 3D printing process of ceramics by thermoplastic extrusion, also known as FDM (Fused Deposition Modelling) using an innovative equipment, recently made available on the market by the company Pollen AM. This study results from the partnership of this company with the Innovation and Development Unit of the CTCV, fulfilling its role of research and technological demonstrations.

Additive Manufacturing of Ceramics by FDM

Additive Manufacturing of Ceramics by FDM

In FDM additive manufacturing technology, an object is constructed by deposition of a bead of molten material produced by an extrusion system, through the formation of layers (Figure 1). It is one of the most widespread technologies for plastic 3D printing, which can also be used for ceramic materials.

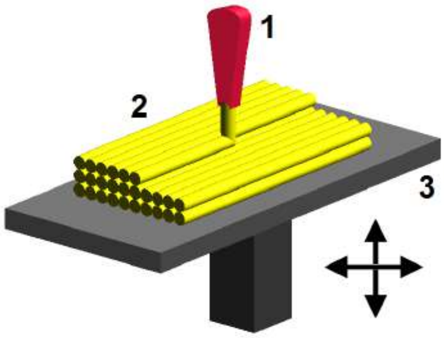

Figure 1 - Schematic diagram explaining the FDM additive manufacturing process.

Before the production process, a 3D CAD model is obtained through software, which must be exported to a proper format - the most common is the STL format. In the preparation phase, from the 3D model, the object construction is set up using slicing software that includes all the printing parameters. The software divides the model into two-dimensional layers (slices) and configures, for example, the selection of the material to be processed, the die diameter of the extrusion head, the print quality, and the movement commands.

The production process then integrates three phases: printing, debinding, and sintering (Figure 2). The raw material consists of a mixture of micronized ceramic material and a thermoplastic. The ceramic material is the material from which the object is to be made. The thermoplastic is a temporary material, which gives the mixture fluidity by heating during the printing process, and is removed from the object in the debinding process. In the last step, the object is sintered when subjected to high temperature, a common process in the ceramic industry.

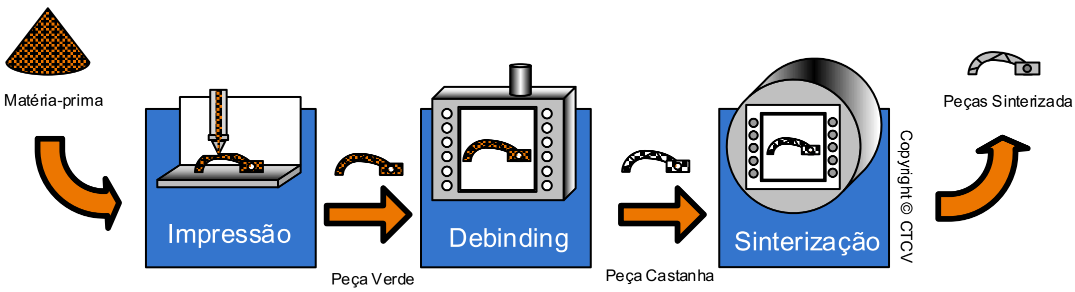

Figure 2 - Production process of ceramic parts by FDM.

PAM Technology

PAM technology (short for Pellet Additive Manufacturing) was developed by Pollen AM, a French company that develops, manufactures and markets industrial multi-material 3D printers (example in Figure 3). The main characteristic of these 3D printers lies in the fact that they use universal materials in pellet form, those currently used by industry. This material format applied to 3D printing gives access to the largest library of raw materials available on the market - standard and performance thermoplastics, elastomers, but also metals and technical ceramics. This specificity makes Pam 3D printers particularly suitable for demanding applications that must meet industry standards.

PAM technology makes it possible to transform certified materials, such as those for skin or food contact, controlled burning for the transport and construction sectors, or for electromagnetic shielding, etc., at an unbeatable cost (granules are 10 to 100 times cheaper than specific materials for 3D printing).
The Pam 3D printer software is also open and allows its users to prepare the print using a set of specific parameters related to the nature of the material to be processed, the parts to be produced and the configuration of the PAM systems - such as nozzle diameter, layer heights, print speeds, process temperatures.

Figure 3 - Pam Series MC 3D Printer from Pollen AM.

Pam 3D printers are equipped with 2 to 4 autonomous and independent extruders. An extruder consists of a hopper (or material cartridge containing granules), a sleeve with an endless spindle, an extrusion nozzle, heating elements, and temperature sensors (Figure 4).

With the rotating motion of the spindle, the granules descend into the extruder where they are melted and compressed. Before being deposited onto the build plate, the material passes through the extrusion nozzle and is extruded through a specific diameter die allowing the bead size to be defined that will make up the layers of the printed part. The movements of the extrusion nozzle relative to the build plate are automatically determined by the system, allowing the part to be created in 3D.

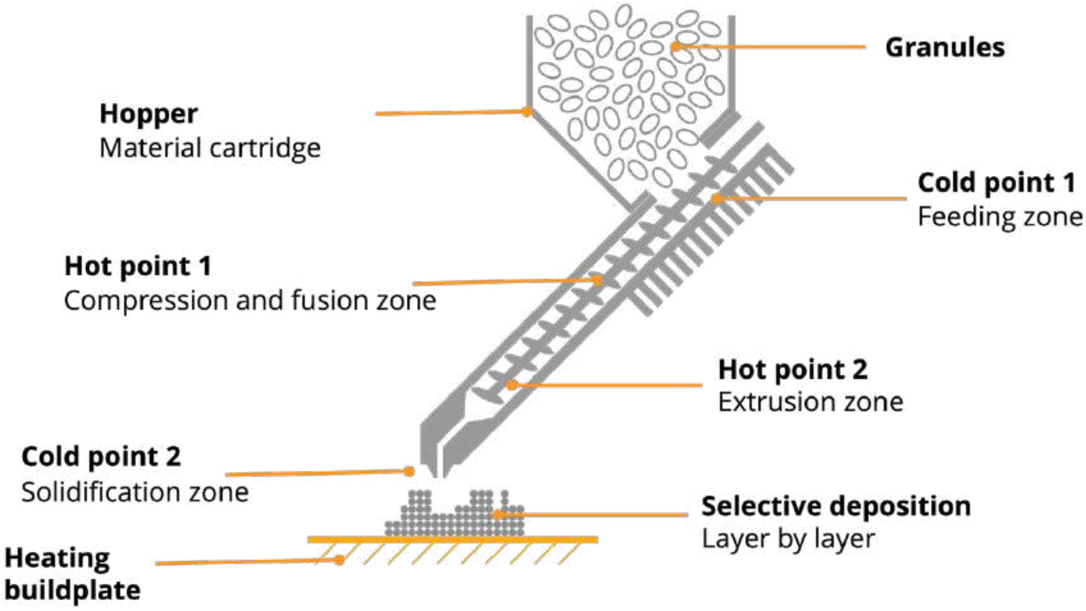

Figure 4 - Pam 3D printer's extrusion melting and deposition system.

Testing the Production Process

To evaluate the PAM technology, a production procedure was performed on two parts that are shown in Figure 5. The valve has geometric details related to its mechanical coupling and functionality, and has outside dimensions of 38 x 8 mm. The insert has a gear geometry and an internal thread, and has outer dimensions of 30 x 20 mm. The geometric details present in the parts represent a challenge to test the technology.

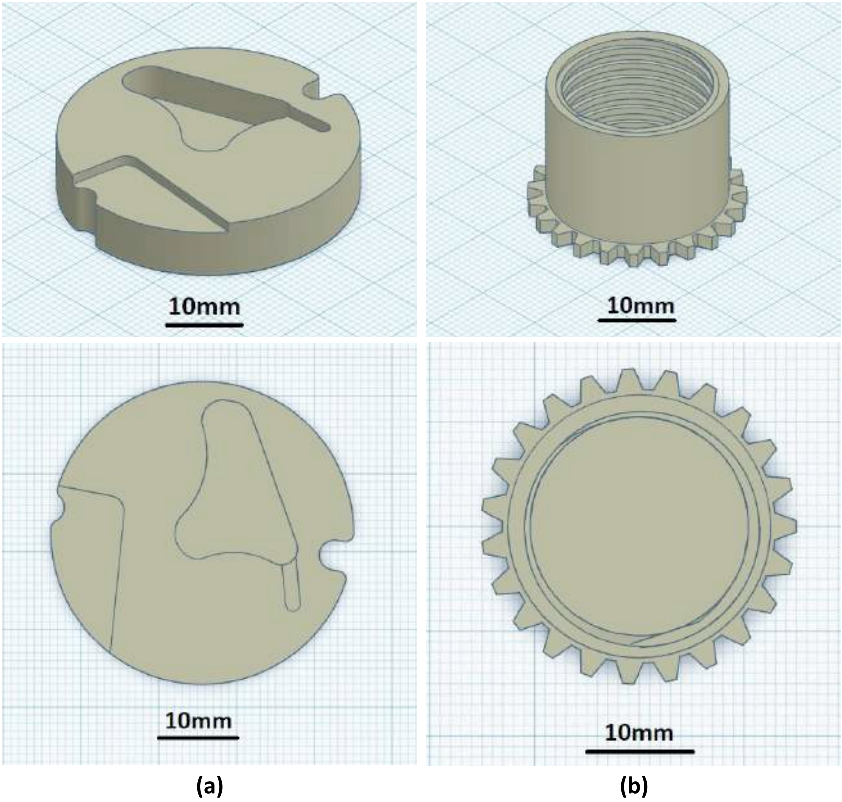

Figure 5 - 3D models of the produced parts - (a) valve and (b) toothed insert.

A CIM (Ceramic Injection Moulding) pellet was used as raw material, with reference Inmafeed K1008 from Inmatec GmbH [4]; it is alumina with 96% of purity. The Pam Series MC printer from Pollen AM was used, with the printing conditions that are presented in Table 1, regarding the extrusion module. The diameter of the extrusion die was 0.4 mm. The build platform was heated to 75 °C, on top of which a 3D printing adhesive was placed to ensure good adhesion of the first build layer.

Figure 6 shows the parts obtained in the printing process, where a good reproduction of shape and geometric details of both parts can be observed. The observed surface quality, which is reflected by the evidence of the construction layers (on the side faces) and the deposited strands (on the top faces) is a characteristic of the process. This process roughness can be adjusted by varying the production parameters, e.g. extrusion die diameter and layer height. On the other hand, adjustments of these parameters have an impact on the printing speed. Higher print quality (resolution) is obtained at the expense of printing time.

Table 1 - Printing parameters.

Temperatures	
Feeding Zone	43 °C
Compression and fusing zone	130 °C
Extrusion zone	188 °C
Build plate	75 °C

Layer Height	0,15 mm
Printing speed	20 mm/s

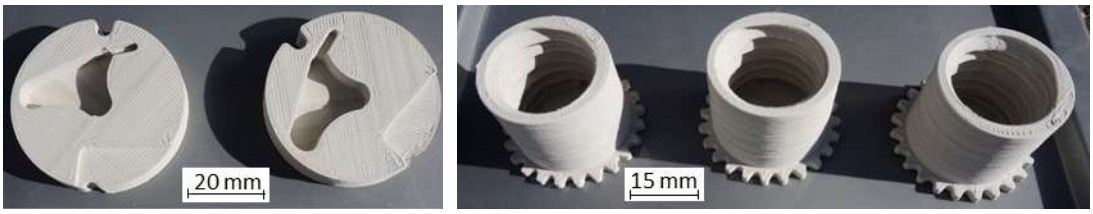

Figure 6 - Printed parts (Green parts).

These green parts were subjected to the debinding process for the removal of the thermoplastic. In the case of the raw material used, this process is subdivided into two steps: the first step consists in an aqueous debinding - the parts are immersed in a water bath with controlled agitation and temperature; in the second step - thermal debinding - the parts are placed in an oven, following a predefined heating cycle (Figure 7). In the first stage, part of the thermoplastic binder is removed, creating a network of channels with open porosity, which facilitates the thermal degradation of the remaining thermoplastic in the second stage. With this two-step process, the goal is to obtain parts free of defects (e.g. warping, cracks, blisters, etc.), especially in thick-walled parts. Once the debinding process is finished, the "brown pieces" are obtained. It was estimated that the plastic loss after the aqueous debinding for 24 hours was 48% of the plastic present in the part, while in the valves it was 25%. This difference is explained by the greater wall thickness of the second piece, 8 mm, compared to the first, 2 mm. The resulting parts kept their geometric details with no defects observed, as shown in Figure 8.

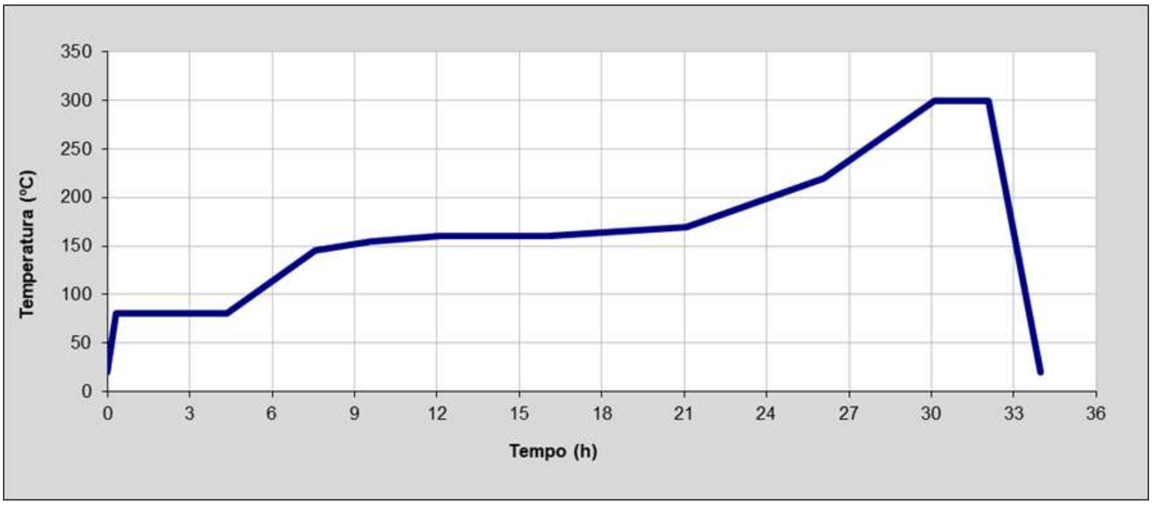

Figure 7 - Thermal debinding cycle.

(a) (b)

Figure 8 - Parts after the two stages of debinding: (a) 1st stage by aqueous debinding; (b) 2nd stage by thermal debinding.

Then, the parts were sintered at 1620 °C for 1 hour, using the thermal cycle shown in Figure 9. The parts obtained showed good shape retention, no deformations, and no structural defects (Figure 10). An evaluation of the part characteristics was performed based on part shrinkage and density, and compared to the specifications of the raw material supplier (Table 2). To calculate the shrinkage of the parts, the green and sintered dimensions were measured.

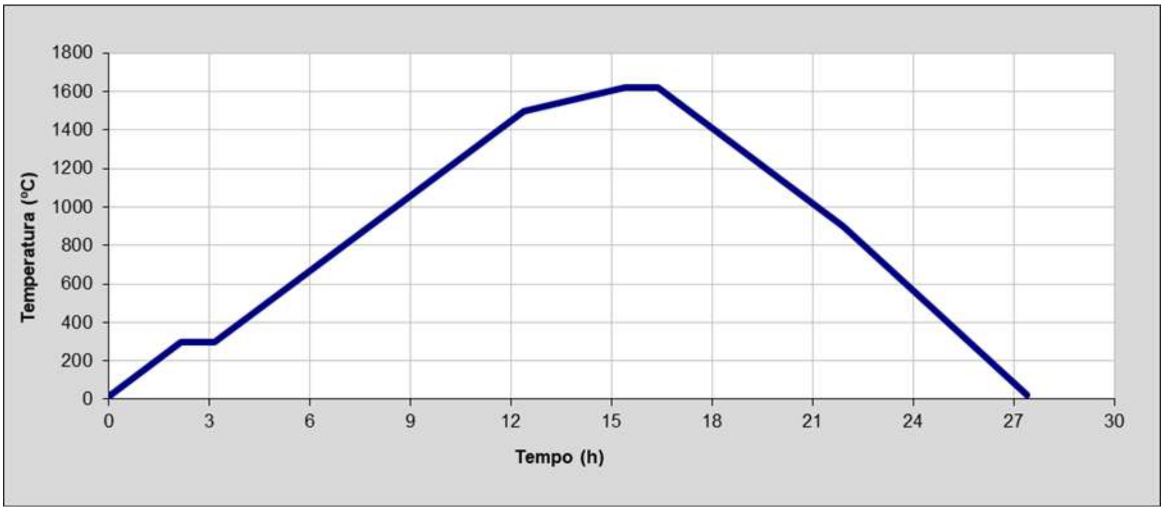

Figure 9 - Sintering cycle.

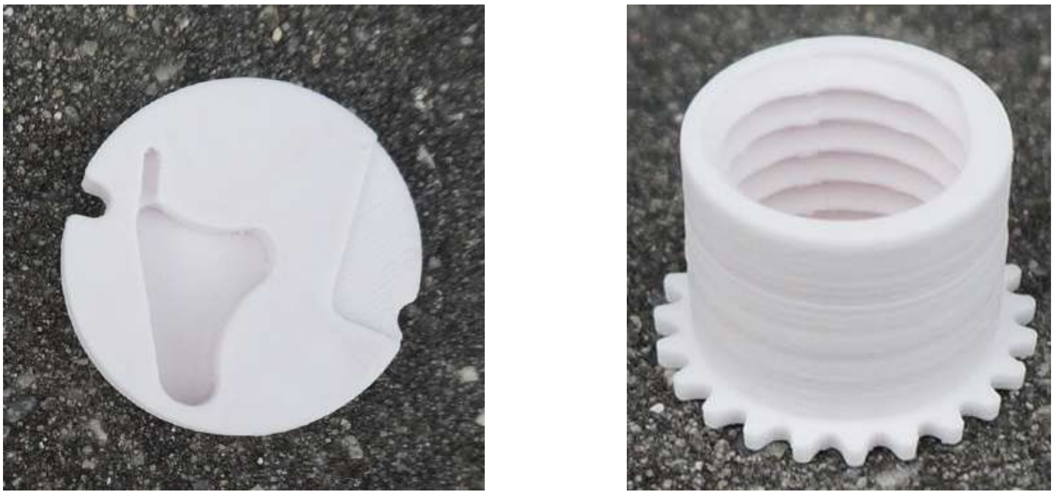

Figure 10 - Sintered pieces.

Table 2 - Characterization of the pieces after sintering.

	General linear shrinkage (%)	Apparent density (g/cm^3)*	Bulk density (g/cm^3)*
Valve	14,8	3,80	3,68
Toothed insert	15,7	3,80	3,63
Raw material supplier [4]	15,5	~3,8	-

* ISO Standard 18754

It can be seen that, in general, the pieces obtained met the specifications of the raw material supplier, both in shrinkage and apparent density. A slightly lower value of bulk density is observed, which normally indicates the presence of open porosity of about 4%. However, it is believed that there may be an effect of the roughness resulting from the printing layers and filaments, a hypothesis that should be studied.

Conclusion

The PAM technology, for additive manufacturing of ceramic parts, was tested on two technical alumina parts. The process used a raw material and some process steps common to an existing production technology. Thus, there is already a production chain that facilitates the adoption of this new forming technology.
In the tests performed, parts were obtained with good shape reproducibility, without structural defects and with a degree of densification as expected. Thus, it is considered a technology with potential to be applied in the technical ceramics segment. As an additive manufacturing technology, it is indicated for the production of parts in small series, with functional and complex geometries, and small dimensions. Shapes that cannot be obtained with other technologies can also be reproduced, as in the example shown in Figure 11.

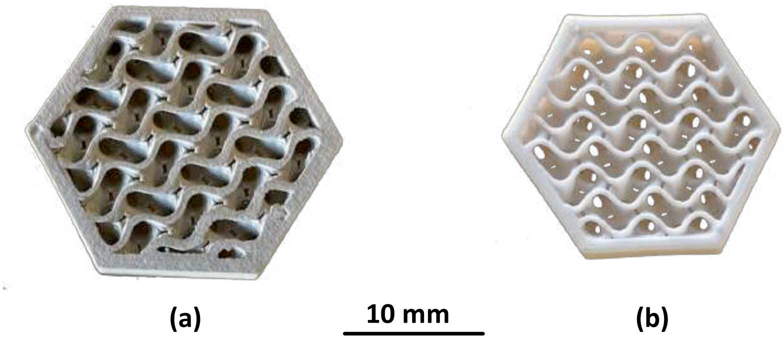

Figure 11 - Ceramic pieces with gyroid geometry - (a) Green part, (b) sintered part.

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