ADAPTING ADDITIVE MANUFACTURING TECHNIQUES TO HERITAGE RESTORATION WITH CERAMIC MATERIALS

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ABSTRACT

This paper presents the main results of the 3DRestaurAM project. This multi-discipline project addresses topics such as the application of 3D technologies for scanning and modelling ceramic pieces, the use of virtual reality, and the formulation of clay-based materials for use in additive manufacturing. The materials developed are applied using what is known as 'Binder Jetting' (BJ) technology. The paper explains the path to be followed to reproduce ceramic pieces, from scanning and printing to post-processing to obtain final parts.

New materials were developed for this additive manufacturing technology and the technical and aesthetic qualities of the end pieces made from the best composition are shown. The parameters given here are final resolution, density, porosity and mechanical (bending and compression) strength of the pieces.

This paper also discusses the milestones reached and improvements required to apply 3D printing technologies (Binder Jetting) to the manufacture of special ceramic pieces.

1. INTRODUCTION

Additive manufacturing (AM), also called 3D printing, comprises a broad group of technologies in which an object is created directly from a virtual model by adding or depositing material, layer upon layer (Figure 1) [1].

The properties of this new model for creating pieces enable the manufacture of new shapes that would be impossible to generate using traditional manufacturing methods, as well as better use of materials, and even the creation of pieces with a multi-material structure. When economic factors and economies of scale are taken into account, AM technology becomes especially attractive for producing unique pieces or small manufacturing batches [2].

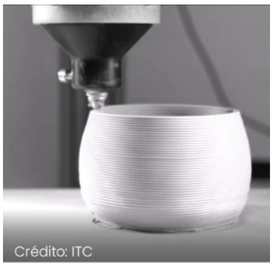


Figure 1 *3D printing of a ceramic piece.*

These features, together with new scanning and reverse engineering technologies, make additive manufacturing an ideal solution for the restoration of objects forming part of our architectural and cultural heritage [3].

Additive manufacturing technologies are in full development in both manufacturing technologies and new materials, although ceramic materials are still a minority (Figure 2) [4],[5].

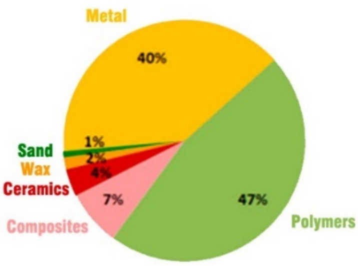


Figure 2 *Materials used in additive manufacturing technologies.*

To stimulate the use of 3D printing or additive manufacturing technologies, new materials adapted to these technologies need to be developed to provide good printing resolution and suitable technical and aesthetic qualities after post-processing [6].

Such is the context in which the **3DRestaurAM** project was born [7]. This multi-discipline project addresses topics such as applying 3D technologies to scanning and modelling pieces, the use of virtual reality, and the formulation of clay-based materials to be used in additive manufacturing technology, all within the framework of creating special ceramic pieces that have a place in the world of architectural heritage restoration and promotion.

Although the term “3D Printing” is typically used as a synonym for all additive manufacturing processes, there actually exist many individual processes that vary in the method of layer manufacturing they use. Individual processes differ depending on the material, the initial state, and the technology of the machine used. The most common classification is based on the characteristics of the additive manufacturing process used, which are taken from UNE-EN ISO/ASTM standard 52900:2017 [8]. According to the standard, they are classified in seven processes: material extrusion, vat polymerisation, material jetting, sheet lamination, powder bed fusion, direct energy deposition, and binder jetting (Figure 3).

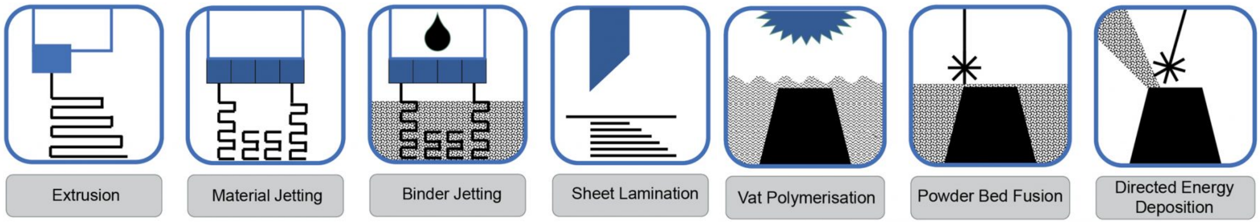


***Figure 3** Diagram of additive manufacturing technology classification (Fraunhofer IGVB).*

Binder Jetting (BJ) [9] is the additive manufacturing technology selected in this study, since it allows for good printing resolution and, at the same time, enables larger format pieces to be manufactured. BJ belongs to the family of powder bonding technologies. Specifically, the technology specialised in ceramic materials started as an MIT project in 1993.

BJ machines consist of two powder platforms: the construction bed and the powder supply bed. Printing a piece begins when the first layer of powder is laid through the roller on the construction platform. Next, a printhead, similar to that used by 2D printers, deposits droplets of liquid (usually the binder) in a 2D pattern that matches the cross section of the 3D model to be printed. After that, the construction platform lowers to the pre-set layer height and the roller deposits a second layer of powder. Each layer adheres to the previous one. This process is repeated successively until the piece is completely formed (Figure 4). Binders can be purely organic or aqueous in nature.

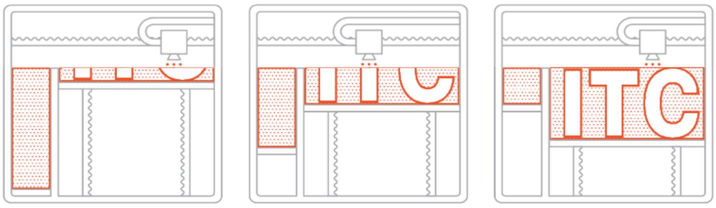


***Figure 4** Diagram of the additive manufacturing process using Binder Jetting technology.*

After printing, the material obtained must have sufficient green mechanical strength to withstand being separated from the powder bed and, when completely ceramic pieces are made, they eventually need to be fired.

2. EXPERIMENT

Figure 5 outlines the process followed to print ceramic pieces: (1) scanning, (2) modelling, (3) data processing, (4) generation of printable files, (5) printing of pieces, and (6) post-processing and firing.

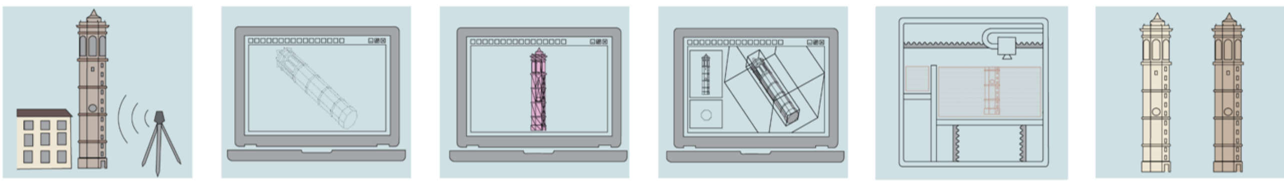


***Figure 5** Diagram of the process involved in reproducing pieces.*

2.1 SCANNING AND MODELLING

Scanning and/or modelling technologies are used to produce files that can be made printable after processing. In this project, both technologies were assessed.

A Topcon GLS 1500 long-range pulse-based Class One 3D Terrestrial Laser Scanner, accurate to 4mm in a scanning range of up to 150m and 6” angular accuracy (2.0 mgon) (Figure 6), was used to make the scans, which were then processed with ReCap point cloud editing software. Various CAD programmes such as Fusion 360 were used for the modelling.

Figure 6 *Ground scanner used*

Using the scanned or modelled pieces, an .stl extension file was prepared. (.stl) is a CAD file format that defines the geometry of 3D objects using tri-angulated surfaces, excluding information such as colour, texture, or physical properties. This file is exported to a slicer programme, where the printing characteristics such as layer height, printing speed, filling, etc. are assigned. The programme is responsible for converting the three-dimensional object into multiple two-dimensional layers (Figure 7) that the machine will be able to interpret.

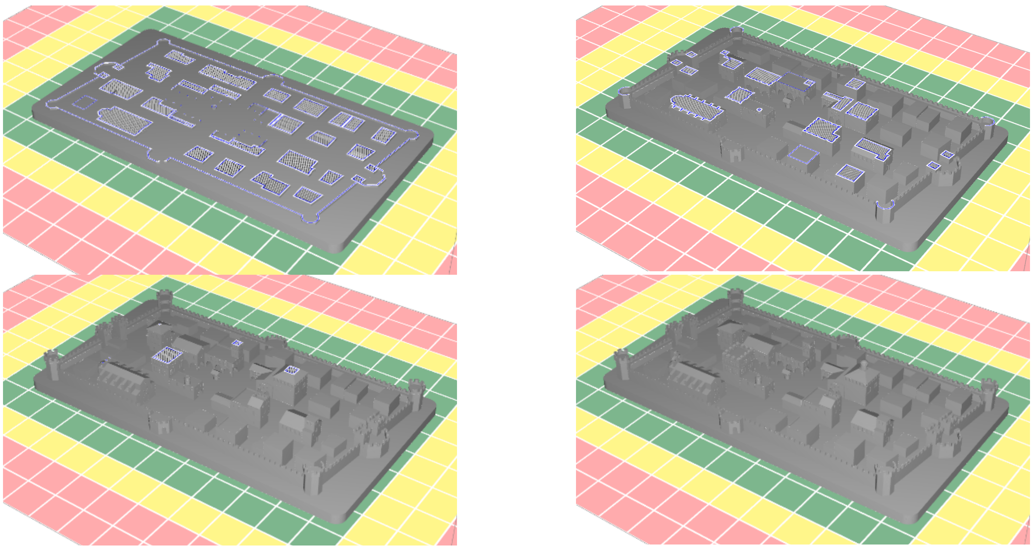


Figure 7 *Slices of a model in different layers*

Virtual Reality (VR) is an environment of simulated scenes or objects that look real. The most common meaning refers to an environment generated by computer technology, which creates in the user the sensation of being immersed in that world.

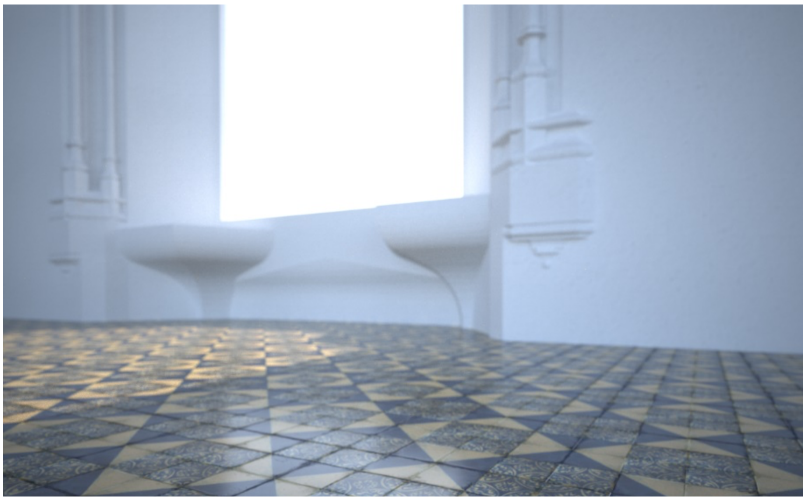


Figure 8 *Virtual Reality of one of the rooms at the Oliva Palace.*

In the case of historic buildings that have been damaged or have even disappeared, with the right tools, they can be restored virtually and displayed. The outcome is an effective depiction, very similar to the original, of the item, which is obtained by applying different textures and looking for points of view, similar to those in a real view, that effectively and sustainably bridge the gap between the virtual space being depicted and the original architectural space [1].

Within the framework of this project, different rooms at the Count of Oliva's Palace, which no longer exists, are displayed in VR. Using these techniques, the impossibility of exploring the palace is suddenly made possible (Figure 8).

2.2 PRINTING

Figure 9 *ZPrinter 310 (ZCorp).*

A ZCorp ZPrinter 310 3D binder jetting printer was used for printing the ceramic pieces (Figure 9). A water-based liquid binder was used (85-95% water). The rest of the components in the binder were additives, such as surfactants or preservatives to produce a viscosity of between 1.1 and 1.3 Pa·s and a surface tension of 72 ± 0.3 mN/m.

To study the mechanical and technical properties of the end pieces made from varying compositions, CAD files were generated with prismatic pieces measuring 80x20x7 mm. The printing parameters are shown in Table 1.

Layer height (mm)	Print speed (layers/minute)
0.1	2-4

Table 1 Printing parameters

The amount of binder varied depending on the area being printed and was higher towards the outer walls of the pieces. The 310 ZPrinter operates in a way that forces a higher concentration of binder to be applied at the edges of the piece, thus creating a strong "shell" around its outside. Inside the pieces, the printer builds an infrastructure by applying a greater amount of binder inside the walls of the piece to create a type of robust "scaffolding".

The rest of the inner areas are printed with lower saturation of binder, which affords them stability but prevents oversaturation, as that can cause the piece to distort (Figure 10).

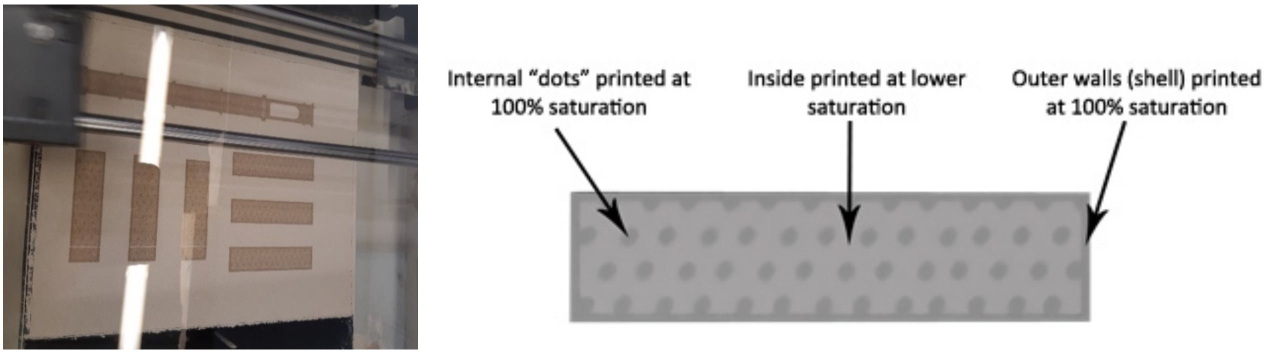


Figure 10 *Detail and diagram of the printing of the prismatic pieces used in the study.*

2.3 MATERIALS

The powder used to prepare the ceramic materials was a typical composition for porcelain stoneware (90-95%). A mixture of organic additives was added to the composition to improve resolution and its green strength. This mixture of compounds is known as 'solid binders', as they also act as bonding agents [6].

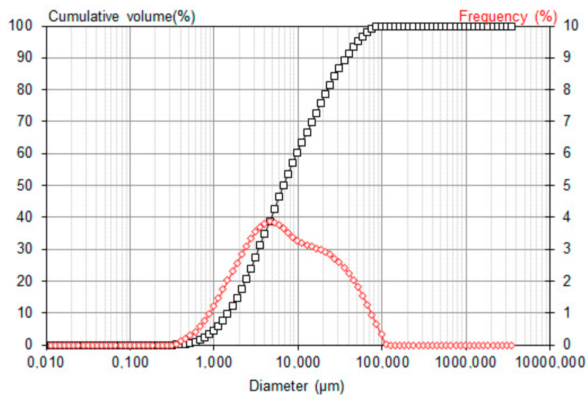


Figure 11 *Particle size distribution of the printing material*

After a process of optimising the printability of the different compositions, the one that provided the best results was selected as optimal. The solid material was prepared dry in a planetary mixer.

The solid mixture that provided the best results in terms of fluidity and with the best resolution had an average particle size of 6.7 ±0.2 µm (Figure 11).

2.4 POST-PROCESSING

Once printing has finished, the entire powder bed in the piece is left to stand in the machine for approximately one hour while the liquid dries. The powder block is then removed from the machine and left to dry in a kiln at 110ºC for 24 hours for the piece to complete the bonding/hardening stage. Subsequently, any excess powder is removed with a brush and/or compressed air. Finally, the piece is sintered in a laboratory muffle kiln at a maximum temperature of 1180ºC to achieve its end qualities.

2.6 CHARACTERISATION OF THE PIECES

To characterise the pieces, the following parameters were evaluated:

2.6.1 STUDY OF DEPOSITION ORIENTATION

To analyse the influence of deposition orientation on printing, a file of twelve specimens was created Figure 12 Six of them were placed parallel to the X axis (aligned with the direction of the printhead), and the remaining six parallel to the Y axis (perpendicular to the direction of the printhead). As mentioned above, piece dimensions were 80x20x7 mm.

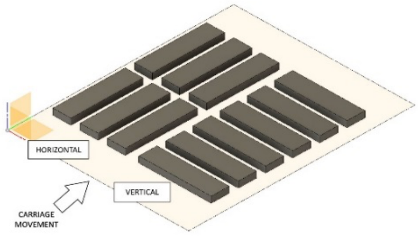


Figure 12 *Print deposition orientation*

2.6.2 STUDY OF DIMENSIONAL ACCURACY

To analyse dimensional accuracy, two aspects were considered:

- Dimensional measurements on prismatic pieces: Samples were measured with a calliper after printing to test the printing accuracy of the process and after firing to determine material shrinkage.

- Dimensional measurements on non-prismatic pieces: To measure the accuracy of non-prismatic pieces, the final pieces were scanned and compared with the printing files.

2.6.3 STUDY OF MECHANICAL PROPERTIES

Flexural strength was determined by bending the pieces at three support points. The tests were carried out on a mechanical testing machine (Instron) at a constant deformation rate of 5 mm/min. The device comprises two bottom support edges (supports), usually cylindrical, and another cylindrical support at the top that applies the load (Figure 13).

To characterise compression strength, files of 10 cubes measuring 20x20x20 mm were printed. The test consists of progressively exerting a normal compressive force on the bases at an application speed of 0.5 mm/min, until they break.

Figure 13 *Bending test set-up with 3 support points*

2.6.4 BULK DENSITY, POROSITY, AND WATER ABSORPTION

The density of the pieces was measured using Archimedes' principle in a container of mercury. The pieces were measured before and after sintering.

Pore size distribution was determined using a Micromeritics AutoPore IV (9500) mercury porosimeter. This technique records variation in the volume of mercury intrusion into the test sample, depending on the pressure applied to it, and transforms that applied pressure into pore diameter values.

Water absorption was calculated by measuring the weight gained by the samples after being subjected to a vacuum pressure of 91 kPa for 30 minutes, then immersed in water, and subsequently kept in water at atmospheric pressure for 15 minutes.

2.6.5 COMPOSITION SURFACE ROUGHNESS BY PROFILOMETRY

This test was carried out with a HOMMELWERKE T8000 roughness tester using a diamond tip probe with a curvature of 90º and radius of 5 μm. On each of the surfaces studied, a topography of 81 profiles measuring 4.8 mm in length and 60 μm spacing between each other was taken, thus covering a surface of 4.8 x 4.8 mm. To calculate roughness parameters, a cut-off of 0.8 mm was used. From each of the profiles thus obtained, roughness parameters Ra and $R_{Z\text{-}ISO}$ were calculated.

3. RESULTS

3.1 SCANNING AND MODELING

To promote the recorded heritage, a website was set up Figure 14, where the files generated in the project are available for free download and reproduction, the different techniques used are explained, and the various pieces created by additive manufacturing with the ceramic materials developed in the project are displayed, amongst other information.

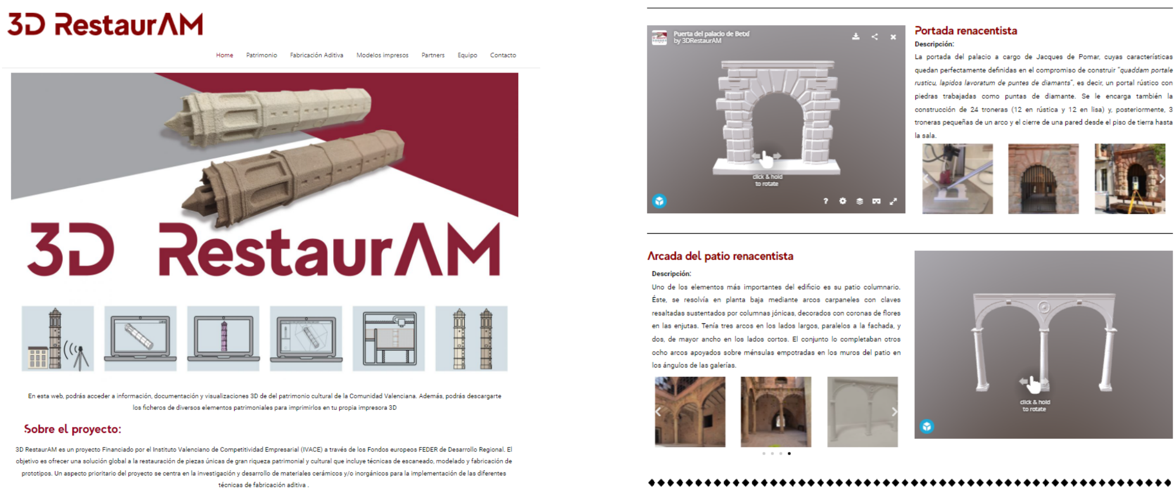


Figure 14 *Project website (www.3drestauram.es)*

To evaluate the feasibility of reproducing the different files, all the models created for the project with various technologies and materials were printed. The technologies and materials used, in addition to BJ, were: Selective Laser Sintering (SLS) with different polyamides, Stereolithography (SLA) with different photopolymerizable resins, and Fused Deposition Modelling (FDM) with different thermoplastic filaments (Figure 15).

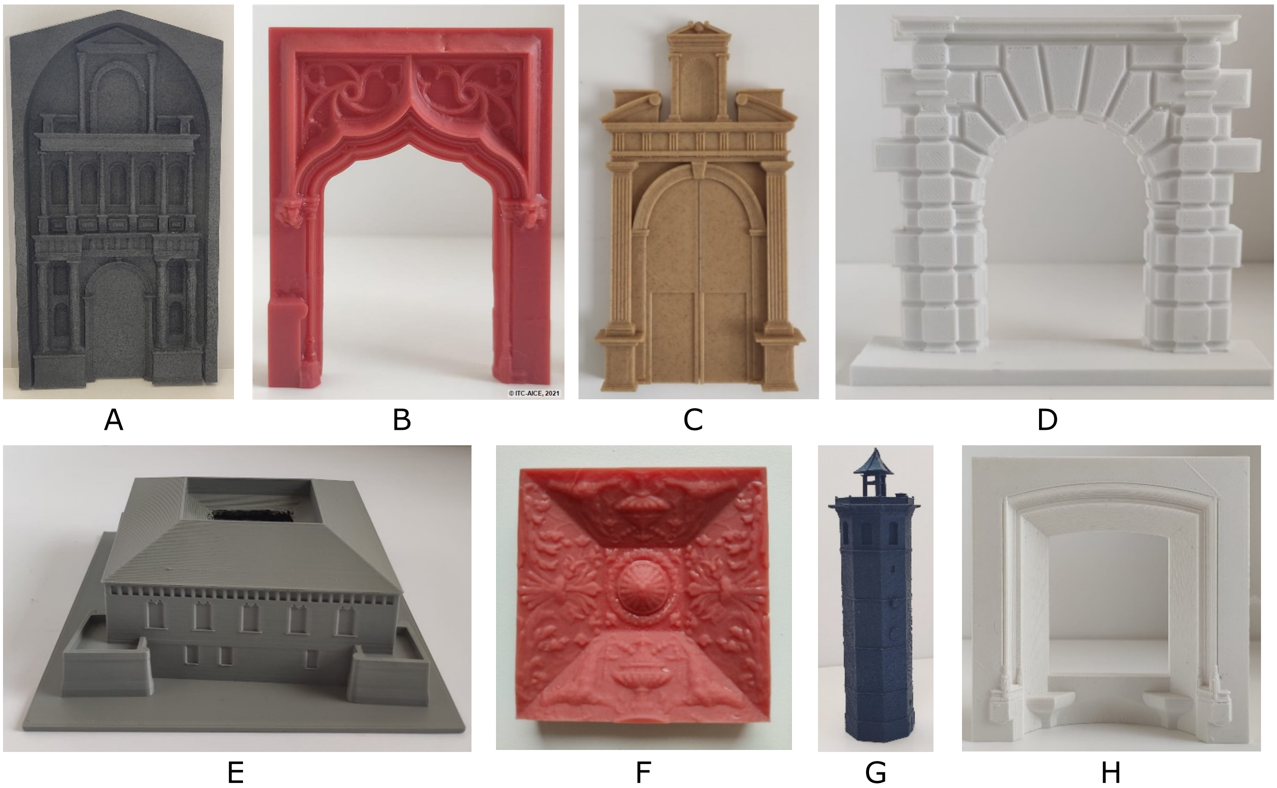


Figure 15 *A) Main façade of the Vistabella church, printed by SLS in polyamide, B) Upper Floor portal at Consulate of the Sea, printed by SLA with photopolymerizable resin, C) Small façade of the Vistabella church, printed by FDM with PLA, D) Door of the Betxi castle-palace, printed by FDM with PLA, E) Castle-palace of Betxí, printed by FDM with PLA, F) Coffered ceiling of the Cocentaina Palace, printed by SLA with photopolymerizable resin, G) Bell tower of Castellón, printed by SLS with polyamide, and H) Window from Oliva Palace, printed by FDM with PLA.*

3.2 PRINTING AND CHARACTERISATION OF BJ-PRINTED CERAMIC TEST PIECES

3.2.1 CHARACTERISATION OF PRINTED TEST PIECES PRIOR TO FIRING

The printed materials were characterised before firing (Table 2.) The parameters evaluated in this case were dimensional accuracy and compression strength. Deposition orientation and its effects on both dimensional and mechanical properties were also studied.

Orientation	Measurements after printing (mm)			Drying shrinkage (%)		
	Length	Width	Thickness	Length	Width	Thickness
Horizontal	77.7 ±0.4	20.0 ±0.3	7.4 ±0.1	2.9 ±0.2	<0.2	5.2 ±0.2
Vertical	77.9 ±0.3	20.2 ±0.2	7.7 ±0.1	2.6 ±0.3	0.9 ±0.2	9.8 ±0.2

Table 2 *Longitudinal measurements and average shrinkage of prismatic test pieces after printing*

As far as dimensional accuracy goes, the resolution was very good, since the original file could be reproduced with an accuracy of over 97%, i.e. longitudinal drying shrinkage in this case was less than 3%.

It is worth noting that the pieces were thicker than specified in the printing file. That is probably due to the slight expansion that takes place in the pieces when the solid binders react with the aqueous liquid.

Furthermore, with regard to print direction, it was seen that the pieces printed in the direction parallel to deposition were longer, whereas those printed perpendicular to the deposition were wider, in both cases the difference was around 0.2%. As a first approximation, for practical purposes, directionality was not a factor to be considered when reproducing the pieces.

The results for green pieces returned an average compression strength of 1.5 ±0.1 MPa. Although the mechanical strength obtained is not very high, it is sufficient to be able to handle the sample and commence the post-processing of the pieces.

3.2.2 CHARACTERISATION OF CERAMIC PIECES

The results of characterising the ceramic pieces printed with the newly developed composition are shown below:

DIMENSIONAL ACCURACY OF THE PRINTED PIECES

Table 3 lists the results of measuring the test pieces after firing and the shrinkage they underwent:

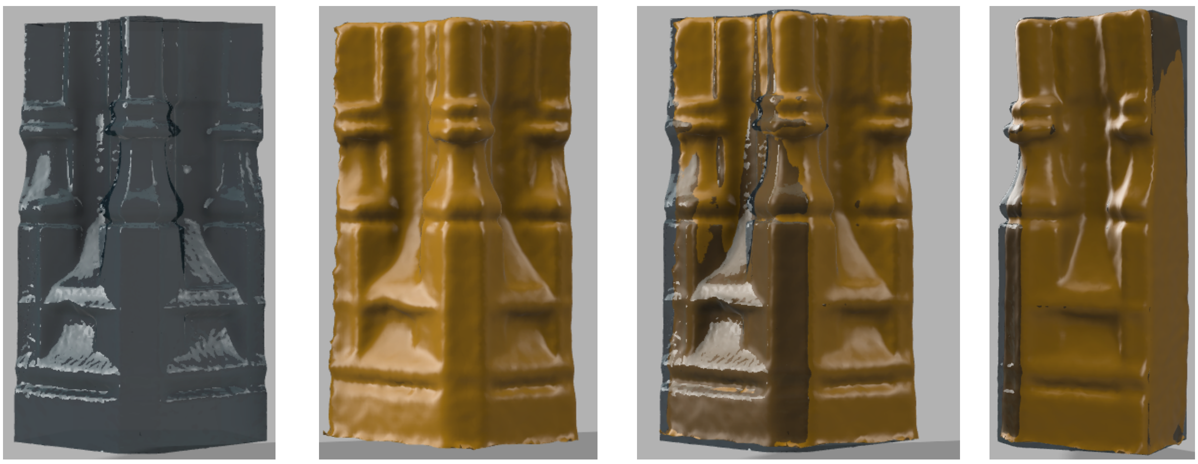
Measurements after firing (mm)			Firing shrinkage (%)		
Length	Width	Thickness	Length	Width	Thickness
71.5 ±0.2	18.1 ±0.1	6.9 ±0.1	7.7 ±0.3	9.5 ±0.2	6.4 ±0.2

Table 3 *Average dimensions and shrinkage after firing the prismatic pieces*

Average shrinkage is approximately 8%, although somewhat higher values can be seen in the wider parts of the pieces. These shrinkage results need to be taken into account in order to redesign the original file and ensure the final pieces have the required dimensions.

DIMENSIONAL ACCURACY OF NON-PRISMATIC PIECES

Figure 16 shows the original scan of a detail of the window of the Cloister of Valencia (A) and the scan that was taken of the piece printed from that file after firing (B). It shows that the geometry obtained is the same, with a high degree of detail; in C) and D), a small difference is noticeable in the overlap of the scans – that is due to a slight curvature caused when the piece was fired. In complex geometries, apart from firing shrinkage, possible deformations taking place during the firing cycle must also be considered. Sometimes, the firing cycle needs to be specially optimised to produce pieces with the required dimensions.



To B C D

Figure 16 *A) Original scan, B) Scan of the printed and fired piece, C) and D) Overlapping of scans.*

FLEXURAL STRENGTH

Table 4 lists the results of testing the printed pieces for bending strength:

Mechanical Strength (MPa)
13.2 ±0.5

Table 4 *Flexural strength of the fired test pieces.*

BULK DENSITY, POROSITY AND WATER ABSORPTION

Table 5 shows the data on the bulk density of both green and fired pieces:

Green bulk density (g/cm^3)	Fired bulk density (g/cm^3)
1.20 ±0.05	1.52 ±0.03

Table 5 *Bulk density of green and fired pieces*

Table 6 porosity data for the fired pieces:

d_{16} (µm)	d_{50} (µm)	d_{84} (µm)	Total pore size (cm^3/g)	Open porosity (%)	Water absorption (%)
58 ±2	35 ±1	15 ±1	0.24 ±0.01	37 ±1	24 ±1

Table 6 *Pore size distribution, open porosity and water absorption for fired pieces.*

As can be seen in the tables above, the resulting bulk density of the fired pieces is not very high, for several reasons: one is the way the powder is deposited, as it is not subjected to compaction, such as by pressing, and another is the internal porosity created by the binding additives added to the composition.

As far as pore size distribution goes, the porosity of the pieces indicates large pores, which impacts negatively on mechanical strength. This porosity may be related to the decomposition of solid binders during firing. Achieving lower porosity and a smaller pore size is the main target improvement being addressed at present.

COMPOSITION SURFACE ROUGHNESS BY PROFILOMETRY

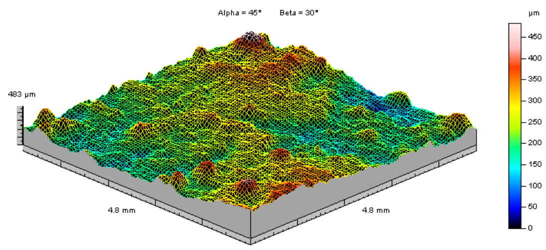


Figure 17 shows a representative topography of those made of the fired prismatic pieces.

shows the mean Ra and RzISO values obtained for the different pieces. The pieces have a surface roughness that is characteristic with this technique.

Figure 17 *Topography of the fired sample.*

Ra (µm)	RzISO (µm)
13.7 ±2.5	72 ±10

Table 7 *Average roughness value of the sample*

3.2.3. REPRODUCTION OF ARCHITECTURAL PIECES

Having created test pieces for characterisation, the question of reproducing pieces with the largest format allowed by the printer was addressed. These concept proofs enable the challenges of scaling to a larger format to be addressed.

Figure 18 shows some of the photos of pieces reproduced at laboratory scale.

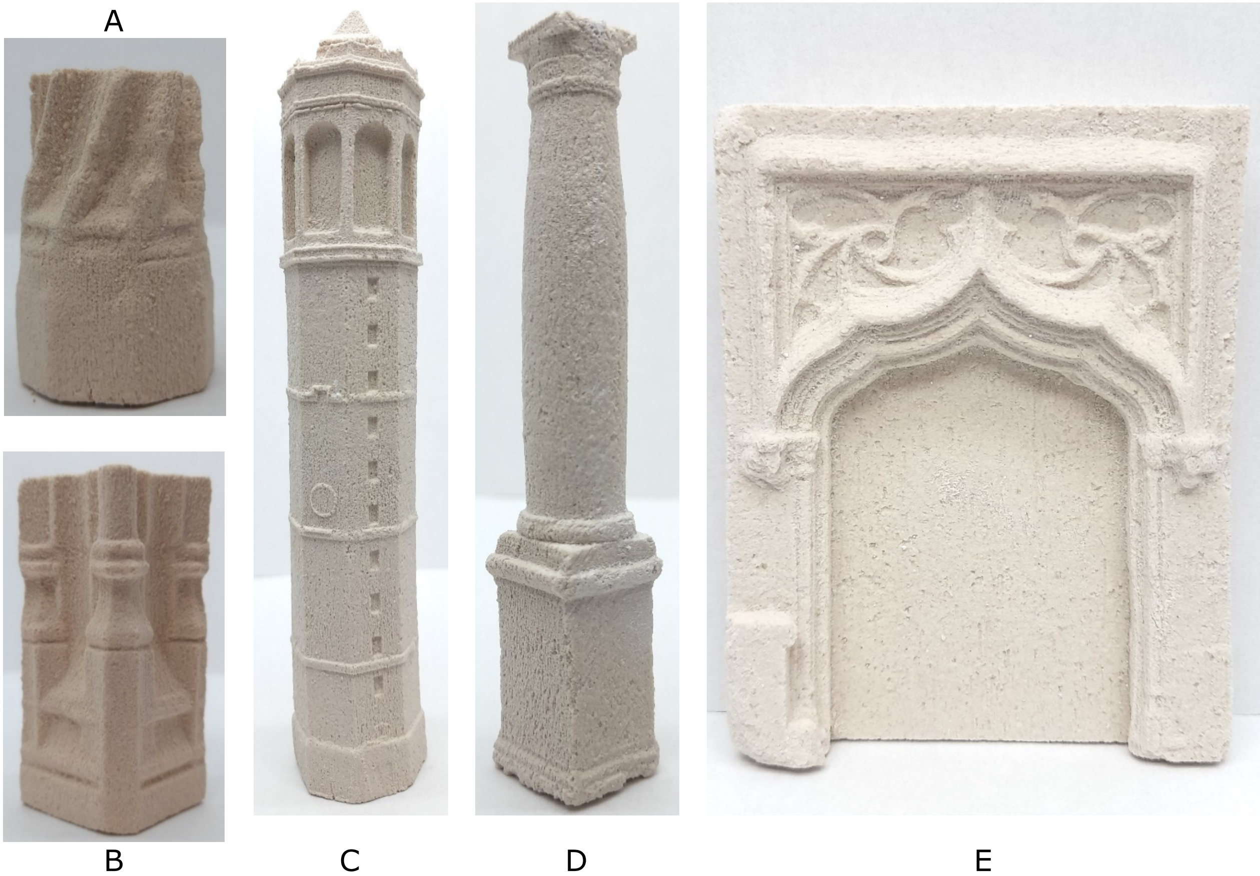


Figure 18 *Pieces made by BJ with ceramic material: A) Base of a column at the Valencia Central Market (Lonja). B) Detail of a window at the Monastery of Cotalba, C) Bell tower of Castellón, D) Column at the Dominican cloisters, E) Portal on the main floor of the Consulate of the Sea.*

4. CONCLUSIONS

The following conclusions can be drawn from this work:

- Scanning and modelling: Digitisation is a tool that helps both to preserve heritage and to make it more accessible. Various pieces were scanned and can be studied, even using virtual reality, and reproduced with different additive manufacturing technologies.
- Composition: A clay-based ceramic composition has been developed that can be printed using Binder Jetting additive manufacturing technology. Although it does not have high green mechanical strength, it is capable of being processed to a very acceptable resolution. The final pieces have high porosity, which affects their mechanical strength when fired. Improvement measures are aimed at reducing post-processing porosity. The end pieces have a rough finish, as is characteristic of the technique used.
- Directionality: The first stage in a study of the influence played by directionality on the dimension of the final printed pieces has been completed. Although the pieces do not appear to have significantly different dimensions, the intention is to research this question further.
- Porosity: Table 6 porosity. This is due, on the one hand, to the organic material decomposing when the pieces are sintered, and on the other hand, to the actual piece creation process, since the material is deposited without any pressing.
- From Figure 18, it can be concluded that the resolution obtained by this material and technique is good, but it is extremely important to correctly adjust the firing cycle to avoid pyroplastic deformation of the pieces.
- The results obtained open the door to upscaling to larger pieces if steps are taken in regard to the binders used to ensure better final porosity in the pieces.

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