# 3D PRINTING TECHNOLOGY AND ITS APPLICATION IN THE CONSERVATION AND RESTORATION OF PORCELAIN

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**ABSTRACT:**

This paper describes the Charter on the preservation of the digital heritage and it also presents the five main printing technologies, FDM (Fused Deposition Modeling), SLA (Stereo Lithography Apparatus), DLP (Digital Light Processing), LCD (Liquid Crystal Display) and SLS (selective laser sintering) technology. Besides, It presents a methodology to process the restoration of a porcelain bowl through three-dimensional scanning and FDM (Fused Deposition Modeling) and LCD (Liquid Crystal Display) 3D printing technologies. First, the porcelain bowl is scanned with the scanner. Then the modeling software is used to reconstruct the missing part that the bowl presents. Finally, the reconstructed 3D fragment model is printed, completed and chromatically reintegrated. In order to optimize this restoration method to achieve the best visual effect similar to the appearance of the porcelain bowl, different printing materials are used for testing. This type of restoration method can improve the final appearance of the intervened area, minimize the operation of the object and can also make it be shaped quickly and precisely.

## 1. INTRODUCTION

Since the birth of 3D printing as a new type of technology that has been applied in many fields, it has also been applied in fields of cultural heritage conservation and restoration. Digital restoration, in professional fields, has been applied for a long time and at different levels in this field ( Escriva Estevan and Madrid García, 2010). Nowadays, digital restoration and 3D printing are developing rapidly due to their high precision and versatility, and are being used more and more in the conservation and restoration of cultural heritage. For example, in the paper “Combining 3D technologies in the Field of Cultural Heritage: Three Case Studies” (Antlej et al., 2011), one of the case studies is an intervention of a bowl with very complex shapes using 3D scanning and printing technology. The procedure is ideal for replacing complex shapes or large missing parts in ceramic objects. In the article “Application of 3D Model of Cultural Relics in Virtual Restoration” (Zhao et al., 2018), the application process of the 3D model of cultural relic in virtual restoration is presented, and the corresponding processes and ideas are verified with the example of the Terracotta Warriors data. When the Terracotta Warriors were unearthed, the surface was painted texture, so excessive contact between the rubble will cause paint peeling, flaking and other phenomena. This virtual restoration method based on the 3D model of the Terracotta Warriors can avoid irreversible secondary damage caused by repeated comparison and splicing debris during the actual repair process. A very famous case, “Innovative uses of 3D digital technologies to assist the restoration of a fragmented terracotta statue” (Arbace et al., 2012), innovative methodologies for the restoration of a terracotta sculpture (Madonna of Pietranico) that was badly damaged after an earthquake were presented.
In general, the introduction of digitized technology in cultural relics protection is a technological revolution in the field of cultural relics protection, which will change the tradition of cultural relics protection technology and means, and even affect the way of thinking and the workflow of archaeologists (Zhao et al., 2018).
Next, it will presents the Charter on the preservation of the digital heritage, the 3D printing technologies and a methodology to process porcelain restoration using 3D technologies.

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## 2. CHARTER ON THE PRESERVATION OF THE DIGITAL HERITAGE

With the development and application of digital technology, the establishment of criteria for the preservation of cultural heritage on computers has become a common demand for researchers from all over the world.
In 2003, UNESCO published the *Charter on the preservation of digital heritage*. The Charter broadens the concept of heritage including cultural works and information products that are “digitally generated or converted from existing sources into digital form.” The Charter is mainly addressed to institutions for the preservation of public knowledge, such as museums, libraries and archives, etc. The Charter affirms the important role of these institutions and recognizes that digital technologies present important opportunities to improve the availability of historical resources. At the same time, the Charter recognizes the risks posed by technological change and emphasizes the need to establish the necessary legislative support for digital heritage. In 2009, the drafting of the London Charter aims to establish general methodological principles for digital visualization applications in the field of Cultural Heritage research and communication. The Seville Principles represent an implementation of the London Charter. They have the value of a Charter, which does not define a system of rules, of laws, but rather the guidelines of a vast scientific community that intends to give impetus to virtual archeology as a mature discipline, which lives in compliance with these rules and is based on scientifically valid and widely shared methods (Gabellone, 2012).
Today, 3D visualization research content in the field of heritage protection is mainly focused on 3D modeling technology, visualization method, and application of software tools.

## 3. 3D PRINTING TECHNOLOGIES

3D printing (3D printing or 3D-P) is a producing process of three-dimensional objects from a digital model that allows the creation of complete objects or parts of objects and machines, through sequential stratification (layering), obtained by placing in sequence, several overlapping layers of materials to make up the object to be produced (Magnaghi, 2015). Nowadays, there are numerous printing technologies， such as FDM, SLA, DLP, LCD, SLS, LOM (laminated object manufacturing), SLM (selective laser melting), FFF (Fused Filament Fabrication), DMLS (Direct Metal Laser Sintering), MSLA (Masked Stereo Lithography) ect., the most common and main technologies are FDM， SLA， DLP, LCD and SLS.

### 3.1 FDM technology

**3.1.1 Technique and material overview:** FDM is the most common 3D-printing technology and it has largely been spread out in the last few years due to the negligible cost of both printers and needed materials (Colella et al., 2021). FDM melt layer molding technology involves heating and melting hot melt filamentary materials, and at the same time, under the control of a computer, three-dimensional nozzles selectively coat the materials on the worktable according to the information of the cross section, and form a layer. Once the formation of one layer is complete, the machine table is lowered one height, and then the next layer is formed until the entire solid shape is formed. FDM technology is an additive technology that releases material in layers.
This technology is most widely used with two plastic filament material types: ABS (Acrylonitrile Butadiene Styrene) and PLA (Polylactic Acid) but many other materials are available ranging in properties from wood filing, conductivity, flexibility etc (Almaliki, 2015). The ABS filament has good hardness and rigidity, and is shock resistant. It is resistant to abrasion and chemical elements. The PLA filament is made up of materials such as corn starch, sugar cane, etc. It is a biodegradable plastic.

**3.1.2 Advantages and disadvantages:**

*Advantages:*
a) The operating environment is safe, and the materials are non-toxic. There is no danger of chemical contamination or toxic gases.
b) Printers and filaments are cheap.
c) The material is used efficiently without waste.
d) The printer is easy to use.
e) It can use a variety of printing materials such as Laybrick, Filaflex, HIPS, HDPE, PVA, PET, Nylon, etc.

*Disadvantages:*
a) After printing, the surface of the model is rough and therefore requires subsequent sanding.
b) Printing speed is relatively slow.
c) During printing a lot of support material is needed.
d) The resolution is low.

### 3.2 SLA technology

**3.2.1 Technique and material overview:** Stereolithography (SLA or SL) is the oldest additive manufacturing technology, and is currently the most advanced which defined the bases of this new type of technology, based on the addition of layers of material to build an object directly from a digital file (Torreblanca Díaz, 2016). It is a light-based process that builds layers of a model with a liquid polymer, and is hardened by a laser beam. It practically uses a laser so that the material hardens when printing. It has a vat full of liquid resin or other material which can be used by this type of system. It also has a base inside with which the model is held. This base rises slowly while the resin is continuously hardened until it achieves its objective (Sanchez Bejarano, 2019). The materials used in the photocuring of 3D printing are photosensitive resin. A photosensitive resin, as its name indicates, is a substance that undergoes changes in its physical properties due to the reaction of light that crosses over it. Generally ultraviolet light (UV), generates a physical differentiation between the exposed and unexposed parts (González Oscullo, 2019).

**3.2.2 Advantages and disadvantages:**

*Advantages:*
a) The development time is longer, therefore the technology has been more tested and is more widely used.
b) High resolution, the surface is very smooth. It can be built into workpieces with complex structures and relatively fine dimensions.
c) Print faster.
d) Larger items can be printed.

*Disadvantages:*
a) Equipment and materials are more expensive. It is also expensive to maintain.
b) It is demanding on the printing work environment, as confined spaces require constant temperature and humidity.
c) Photosensitive resin is slightly toxic and pollutes the environment.
d) Fewer types of materials available for printing.

### 3.3 DLP technology

**3.3.1 Technique and material overview:** DLP technology emerged more than ten years after the emergence of SLA technology. The DLP technique is a method of producing a prosthesis through photo-polymerization by irradiating UV light to a tank containing acrylic or epoxy-based light-curing resin that reacts to ultraviolet rays (UV) (Moon et al., 2021). DLP uses a projector to project the image of the cross section of an object into photosensitive liquid resin. Each image layer is cured by light-curing in the thin area of the resin layer to form a thin layer of the part. Normally, the free radical photosensitive resin is used for DLP 3D printing (Quan et al., 2020).

**3.3.2 Advantages and disadvantages**

*Advantages:*
a) The DLP technique is fast in printing and guarantees high precision. It also has a good quality, it can be used to make relatively fine parts.
b) The high contrast, the absence of remanence in the images and the ease of adjustment. (Derré, 2014)
c) The low cost of this type of technology and the long useful life of the LED light source mean that the overall cost of printing is low due to energy savings.

*Disadvantages:*
a) The loss of brightness, its high price, the heat and noise emitted by the system as well as the short duration of the lamp. (Derré, 2014)
b) DLP printing technology cannot print large objects.
c) Resin material is expensive, but the strength, rigidity, and heat resistance after molding are limited, which is not conducive to long-term storage.

### 3.4 LCD technology

**3.4.1 Technique and material overview:** LCD technology is slightly later than DLP technology. In all photocuring 3D printing technologies, from laser scanning SLA, to DLP digital projection, then to the latest LCD printing technology, the main difference is the light source and imaging system. The big difference between DLP and LCD 3D printing technology is the imaging system. The working principle of the LCD 3D printer is to use the LCD image principle of the LCD screen. Driven by the computer and the display circuit, the computer program provides the image signal. A selective transparent area appears on the LCD screen. Ultraviolet light passes through the transparent area and irradiates the resin. The photosensitive resin in the vat are exposed and cured, and the curing time of each layer ends. The platform lifts the cured part to let the resin liquid flow out, and the platform falls again and the thin layer between the mold and release film is again exposed to ultraviolet light. The process is repeated until the object is completed. Normally resins used in DLP printing or most photocurable resins can theoretically be used in LCD printing.

**3.4.2 Advantages and disadvantages:**

*Advantages:* a) LCD machines are cheaper compared to SLA and DLP.
b) High printing precision.
c) High resolution.
d) The printing speed is faster than in the case of FDM printing.

*Disadvantages:* a) The LCD printing platform is small and cannot print large-volume models.
b) The LCD printer film is easy to be aged, it is a consumable part and the film should be replaced frequently.

### 3.5 SLS technology

**3.5.1 Technique and material overview:** Selective laser sintering (SLS) also refers to laser sintering. It is a technology which melts the powder materials directly by laser energy to construct three-dimensional parts (Wang et al., 2020). The laser selectively fuses the powdered material by scanning the cross-sections (or layers) generated by the 3D modeling program on the surface of a powder bed. After each cross section is scanned, the powder bed is lowered by one layer thickness. Then a new layer of material is applied on top and the process is repeated until the object is completed (Almaliki, 2015). Selective laser sintering is a leading-edge rapid prototyping and additive manufacturing technology that can generate finished quality parts directly from computer-aided design (CAD) models or stereolithography (STL) files of an object, thus saving significant amount of time and expense. SLS technology has a variety of materials for its printing, such as polymers, metals, ceramics, plaster, nylon and other powdered materials. The main printing materials are thermoplastics, metal powder, ceramic powder, glass powder etc.

**3.5.2 Advantages and disadvantages:**

*Advantages:* a) A wide variety of materials can be used.
b) It has high precision.
c) A support structure is not required. The layer suspended during the process can be directly supported by the unsintered powder.
d) It has a high material utilization rate. Since there is no need for support, there is no need to add a base, thus it influences the material utilization rate, which is the highest among the most common 3D printing technologies.

*Disadvantages:* a) The surface is rough. Because the material is powdery, the prototype is built by heating and melting the powder layer of the material to achieve a layer-by-layer bond. Therefore, the surface quality of the model is not high and the resolution is low.
b) It has a very marked odor during the sintering process. In it in the SLS process, the powder layer needs to be heated by a laser to reach a molten state, and the polymeric materials or powder particles volatilize a gas during laser sintering.
c) Due to the use of high power lasers, in addition to the cost of its own equipment, it also requires a lot of auxiliary protection processes. The general technical difficulty is high and the manufacturing and maintenance costs are high.

Through the comparison and analysis of five different printing technologies, we decided to use FDM and LCD two printing technologies in this study, considering comprehensive factors such as the cost of printing, the degree of difficulty, and the visual effect of implants.

## 4. METHODOLOGY TO PROCESS PORCELAIN RESTORATION USING 3D TECHNOLOGIES

Porcelain represents the foundation of the ceramics discipline and one of the most complex ceramic materials (Carty and Senapati, 2005). It is a brittle material with a high risk of fracture due to tensile stresses and has little elasticity. During the stage of reconstruction of missing parts carried out in porcelain restoration, it is usual to apply molds and resins to reproduce lost areas. However, the traditional method has some problems because it must be operated directly on the surface of porcelain, which has a more or less impact on it, such as the presence of deposits or residues of contaminated products (such as silicone rubber, plasticine or others). 3D reconstruction and 3D printing can successfully solve these problems by intervening indirectly without contact. This kind of mold forming method not only saves materials, improves material utilization, but also can be formed quickly and accurately.
In this study, a broken porcelain bowl is selected for research (Fig. 1).The process is carried out with a scanner. Based on the acquired data, the 3D reconstruction is designed by virtual modeling of the missing fragment. The reconstructed virtual fragment is printed with technologies FDM and LCD. The process is as follows: 3D acquisition, creation and modeling of the implant, 3D printing, surface treatment of the implant, chromatic reintegration.


**Figure 1.** Porcelain bowl, front view

### 4.1 3D Acquisition

A 3D scanner is a physical device. It can generally obtain a cloud of points that digitally describe the shape of a real-world object in three dimensions after the implementation of hardware, software and specific techniques (Calyecac Marreros, 2009). In this study, the EinScan-SP scanner is used (Fig. 2). This is the structured light 3D scanning technology.This type of scanner has two scanning modes: Fixed Scan（With Turntable） and Fixed Scan （Without Turntable). In our case, fixed scan mode (with turntable) was selected. Fixed scanning (with turntable) is very useful since it has a system with a rotating platform that is used to generate the rotations so that the scanner can scan the object from various angles. The object must be placed with the different positions. Data acquisition is accomplished through a series of scans that generate point clouds. Every scan cycle can set the scan times per round under turntable scan, which depends on how many scans are required. In our study, the setting of the bowl is 32 times and the align mode is turntable. Every time a scan cycle ends, the software that manages the scan must clean the cloud of points, that is, from the cloud of points in the scan cycle, remove those that are not in the body of the bowl. Finally, the model is exported and saved in STL format (Fig. 3).

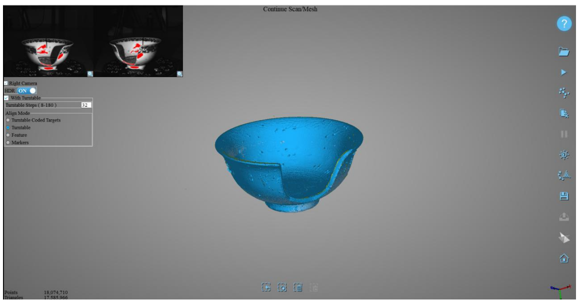


**Figure 2.** Bowl Mesh during the scanning.

**Figure 3** Bowl 3D model, front view

### 4.2 Creation and modeling of the implant

3D modeling is a special description and placement of three-dimensional objects, scenes and environments with the aid of a computer (Charro Arévalo and Valencia Armijos, 2007 ). In this study, the modeling of the missing part is modeled from the original object. Once the model has been exported, then imported into Meshmixer software, taking advantage of the symmetry of the object, an area with sufficient size is selected (Fig. 4), which allows the missing part to be covered, then the model and the selected area are exported to the Blender software. The 3D model of the original object and the model of the selected area are aligned, and then the option Boolean (Difference) is applied (Fig. 5). For errors in the details of the modeling, manual modifications are made in the Blender software to obtain the model. Finally, the obtained implant is exported in STL format for 3D printing. (Figg. 6-7).

**Figure.4** Sectioned area for implant

**Figure. 5** Boolean option

**Figure. 6** 3D Model and implant

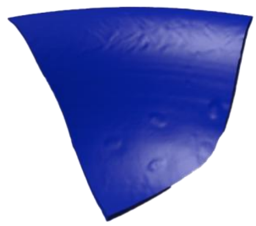


**Figure. 7** 3D implant

### 4.3 3D print

**4.3.1 Implant printing with FDM technology:** Printing using the ANYCUBIC Mega-S printer and the 1.75mm white "ceramic" PLA filament. "Ceramic" PLA is a mixture of ceramic particles (15% by volume) and NatureWorks Ingeo PLA (85%). Once STL file is prepared, it is imported into Ultimaker Cura software for slicing. To carry out a 3D print, it is necessary to indicate a series of parameters. The layer height varies between 0.05mm - 0.3mm, the lower the layer distance, the higher the resolution, that is, the higher the object quality. Otherwise, the higher the layer distance, the lower the resolution, in the lower the object quality. According to different layer heights, a series of tests are carried out (Tab. 1).
In this study, because the bowl implant is very thin, filling density is set at 80%. The higher the fill density, the more consumables there are and the longer the print time. The printing speed of PLA material is between 20mm/s-50mm/s. If the speed is excessive, the part may print badly. During printing, to add the supports is needed. Finally, export and save in .gcode format for printing.

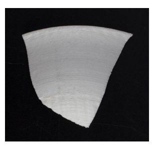
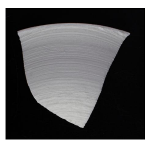
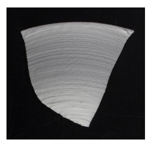
| Implant tests |  |  |  |
|---|---|---|---|
| Resolution (mm) | 0.1 | 0.2 | 0.3 |
| Price (€) | 0.49 | 0.54 | 0.59 |
| Consumable weight (g) | 16 | 18 | 20 |
| Time (min) | 340 | 189 | 141 |

**Table 1**. Print tests with different resolution


https://doi.org/10.5194/isprs-annals-X-M-1-2023-301-2023  

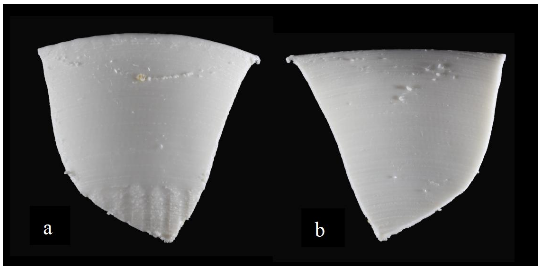



**Figure 8**. Result of 3D printing of the implant.
a: external face view. b: internal face view

**4.3.2 Printing of implants with LCD technology:** The print has been developed with a Creality 3D LD-006 printer and a white resin sensitive to UV radiation. The 3D printing of a resin piece is much more dangerous compared to printing with traditional filament.

Once the scan STL file is prepared, import it into the Chitubox software for slicing. Comparing to the FDM technology, this technology works on the images, therefore, each image like the projection time, how many seconds, remains on the screen, follows the resin. After adjusting the parameters, save in .ctb format for printing.

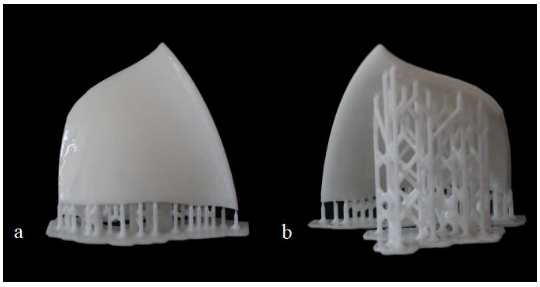



**Figure 9.** Result of 3D printing of the implant.
a: external face view. b: internal face view

### 4.4 Implant Surface Treatment

In our study, using two printing materials, each printing material has a different post-processing.

**4.4.1 Surface treatment of PLA filament implant:** The 3D model that is printed by FDM is shown on its surface with different layers that form it. In the first place is to correctly remove the supports. Afterwards, the prototyped implant is manually sanded with abrasive papers of different weights and files, both dry and wet (with water). Thanks to the characteristics of this type of filaments, the surface of the printed implant has been easy to sand, resulting in a very smooth surface (Fig. 10).

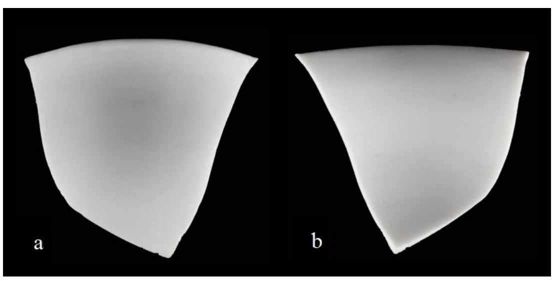



**Figure 10.** Result of the superficial treatment of the implant.
a: external face view. b: internal face view

**4.4.2 Surface treatment of the resin implant:** The 3D model that is printed by LCD shows its surface is already very smooth. Once the printing is completed, residue and excess resin remain on the printed implant. For post-processing, a machine is used to clean all the residue and then an ultraviolet light bath to stabilize all the polymerized resin. This machine has a double function. On the one hand it is a machine that has a container. This container is poured with 99° isopropanol, which is a very pure alcohol that will clean the entire surface of the printed implant. It takes about three minutes to clean. Once the printed implant has been cleaned, the container is removed and the printed implant is placed on a rotating platform of the machine to make a 360° bath of ultraviolet light to stabilize all the cured resin from all angles. Then with the help of a small pliers, remove all the supports carefully. When the entire support structure has just come out, for the areas where there is still a little liquid, the printed implant can be submerged again in the isopropyl alcohol. Finally, files and abrasive papers are used to sand the marks left by the supports (Fig. 11).

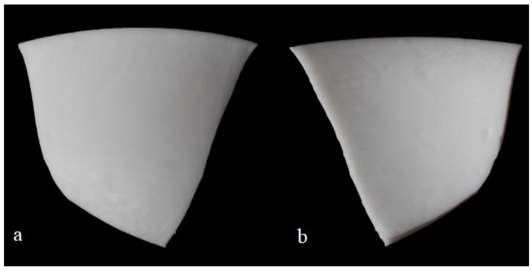



**Figure 11.** Result of superficial treatment of the implant.
a: external face view. b: internal face view.

### 4.5 Chromatic reintegration and incorporation into the porcelain object

"Chromatic reintegration" is a decisive intervention process for the final result of art restoration (Mercado Hervás, 2004). According to the principle of the Restoration Césare Brandi, integration should always be easily recognizable, but not necessarily undermining the unity of its reconstruction. (Brandi, 2000).

Once the implant is polished, the transparent “Primer spray” is applied on this prototyped fragment, waiting for the resin to dry completely. In the final stage, the implanted print is bonded to the bowl with a compatible adhesive (e.g. Uhu plus) and finally colored with acrylic pigments (Figg. 12-14). Before applying paints, a series of tests are carried out with PLA "ceramic" filament to locate the color closest to that of the original surface.

**Figura 12.** Porcelain bowl after chromatic reintegration with PLA “ceramic” filament; view of the base


**Figura 13.** Porcelain bowl after chromatic reintegration with PLA “ceramic” filament; top view.


**Figure 14.** Porcelain bowl after chromatic reintegration with Pla “ceramic” filament; front view.

## 5 CONCLUSIONS

This paper discusses the Charter on the preservation of the digital heritage and introduces and summarizes the five main printing 3D technologies. At last, this study proposes a restoring method, which uses a new 3D technology to scan the porcelain bowl in 3D, then virtually model the missing part of the porcelain bowl, and reconstruct the volume of the missing fragments. The biggest advantage of this technology is that it is non-invasive. Because compared with the traditional restoration, it can not make direct contact with the object, so it will not leave residues, so as to avoid the possible secondary damage to the porcelain in the restoration. In order to perform 3D implantation, different technology with different materials are used to optimize the steps. "Ceramic" type PLA filament has excellent resistance and stability. On the other hand, the resin material presents a very smooth and high-precision surface and ideal light transmittance.

These two printing technologies are the most suitable for the application in porcelain restoration. Next, the two technologies will be compared and analyzed from the following aspects:

**Economic cost:** Both printers used in this study are relatively inexpensive, the FDM printer is cheaper compared to the LCD printer. The cost of two printing materials is more or less.

**Operating environment:** FDM technology is safer, and printing materials are non-toxic. However, the sensitive and light-curing resin in the presence of UV radiation is slightly toxic and pollutes the environment.

**Surface resolution:** The filament printing surface has a low resolution. The model surface is rough, and needs to be sanded. As for the resin used as printing material, providing a very smooth surface, ideal light transmission and good surface quality. The resolution is very high, which can reach the micron level.

**Printing process:** The FDM printing process is relatively simple. Import the file into slicer software, and after the supports are automatically generated, you can start printing. After printing, remove the supports and then sand it down, then the printing process is basically completed. However, LCD printing is more complex compared to FDM. After printing, it should be cleaned with alcohol, bathed in ultraviolet light,removed the supports and sanded the marks left by the supports. Then it is necessary to clean the build platform and resin vat, and the whole process is considered complete.

Therefore, the new 3D technology plays an important role in the conservation and restoration of porcelain cultural property.

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