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Review

Additive Manufacturing to Produce Complex 3D Ceramic Parts

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Abstract

Attempts to improve the performance of ceramic parts have recently led to advances in their design and in the processes used to tailor these parts. Thus, Additive Manufacturing (AM) technologies, initially developed in the polymers and metals industries, have become of increasing interest for shaping ceramic parts. Among AM techniques, photopolymerization (referred to as stereolithography (SLA) and micro-stereolithography) makes it possible to reach high accuracy that matches the design requirements for new applications of ceramics in a wide range of fields. The development by means of (micro)-stereolithography of complex 3D ceramic parts with improved performance requires the mastering of various parameters linked to the inorganic-organic system involved in this processing route. This paper reports on some recent achievements in the production of ceramics using photopolymerization. Some examples of the work performed at the SPCTS laboratory to produce complex 3D ceramic parts for applications in the fields of information and communication technologies, healthcare and jewellery are presented.

Keywords: Shaping, additive manufacturing, photopolymerization, stereolithography

I. Introduction

Since their introduction in the late 1980s, additive manufacturing technologies (AM) (or Solid Freeform Fabrication (SFF)) have become the most commonly used methods to produce accurate low-cost prototypes within a short time, via an automated process. The prototype is directly built up from a computer-aided-design (CAD) file, allowing the user to respond immediately to the shape, function or performance of the model, which is an accurate reproduction of the CAD file ^{1,2}. The additive methods generally use a layer-by-layer fabrication procedure ³. The starting step of any of these methods consists in faceting the three-dimensional object by converting its CAD file into a standard STL (STereoLithography) format ^{4, 5}. The object is then sliced into several parallel successive crosssectional layers, the distance between each layer being equal to the thickness of a layer. This way to produce threedimensional parts makes it possible to obtain complex geometric shapes, such as cavity or included shapes, which cannot be produced with traditional methods. The development cycle of a product can be drastically reduced, as errors can be detected on the prototype, directly corrected on the CAD file and checked on a new prototype, before production, reducing the risk of costly changes afterward.

In the past few years, additive manufacturing techniques have attracted increasing interest in several countries around the world mainly owing to the wide possibilities they offer: in his 2013 address to the State of the Union, President Obama highlighted their "potential to revolutionize the way we make almost everything" and announced the opening of an institute specialized in AM, i.e. the National Additive Manufacturing Innovation Institute in Youngstown, Ohio. In China, the AM techniques industry is also exhibiting notable growth. In Europe, several groups are dedicated to the promotion of AM technologies such as the European Additive Manufacturing Group created in May 2013 (specialized in AM technologies for metals).

The technique has now been developed to become a real production tool in various industrial fields, but mainly in the domain of polymers (Fig. 1)⁶. Depending on the nature of the final object, the AM techniques can also be used to produce a cost-effective single item or for lowvolume manufacturing. The metallurgy industry uses AM techniques to build master moulds that are used in several moulding processes such as injection moulding or investment casting. AM techniques also appear particularly

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useful for three-dimensional reconstruction or reproduction of archaeological objects, or in the biomedical industry with the realization of on-demand implants for craniofacial or dental surgery. Many other domains of applications, for instance in the automotive and aerospace industry, or in Information and Communication Technologies (ICT), can be also cited.



Fig. 1: Different applications of rapid prototyping techniques applied to polymeric materials, from H. Liao⁶.

Several AM methods to shape three-dimensional ceramic parts have been adapted from those initially set up for polymers and metals. Ceramics have specific properties such as low density, high thermal resistance (mechanical properties maintained at high temperature), chemical neutrality, high hardness or functional properties (electric, optical, magnetic...) that are of prime interest for certain applications. Ceramics parts are usually manufactured by dispersing the ceramic powder in a more or less complex organic medium, creating an organic-inorganic system (suspension, feedstock...), which is then shaped and consolidated by means of thermal treatment ⁷.

AM techniques, such as sheet lamination, powder bed fusion, material/binder jetting, material extrusion, and photopolymerization, allowing the creation of ceramic parts without moulds or tooling are currently used or under development to build three-dimensional ceramic parts. The most common ones are presented below, according to the standard terminology ^{4, 5}.

Sheet lamination (or Laminated Object Manufacturing) technique was first reported in 1984 by Kunieda⁸. It consists in building parts by laminating and laser-trimming the material delivered in sheet form (paper or plastics). Each sheet is coated with a thermally activated adhesive. The upper sheet is cut with a CO₂ laser and laminated onto a previous sheet by heating. The process is repeated until the object is fully formed. The use of this technique for ceramics fabrication (alumina and zirconia) was reported in 1994 by Griffin ⁹, using tape-cast ceramic sheets.

Powder bed fusion was proposed by Deckard ¹⁰ in 1986, then patented in 1989¹¹. It consists in building threedimensional parts by melting selected areas of the surface of a powdered thermoplastic material with an IR laser. This technique previously used for organic materials (polyvinyl chloride, polycarbonate, wax, nylon...) was extended to the selective laser sintering (SLS) of metals (copper, aluminium, bronze...) and ceramics (alumina, silicon carbide, silica) ^{12, 13, 14}. **Binder jetting** consists in the consolidation of a deposited powder bed by jetting a binder. A jetting head deposits a binder to bond ceramic particles in the defined pattern. After the part is completed layer-by-layer, the embedded cohesive 3D part is removed from the unagglomerated powder particles. As an example, this technique was used to build ceramic shells with silica and alumina powders joined by a colloidal silica binder ^{15, 16}.

Material jetting (or inkjet printing) was developed by depositing tiny drops of melted material (thermoplastic) onto a surface, making it possible to obtain high accuracy and surface finishing. Once deposited the material cools down and solidifies. For ceramic applications, inkjet printing consists in the deposition of small droplets of a ceramic dispersed in a thermoplastic material, of a ceramic suspension or of ceramic precursors, generally by means of a piezoelectric nozzle ^{17, 18}. The deposition is controlled by moving the head before ejection. Inkjet printing is mainly used for making electronic components.

Material extrusion (or Fused Deposition Modelling) was developed by S. Scott Crump ¹⁹. During the building process, a filament of thermoplastic material is introduced into a temperature-controlled extrusion nozzle. The fused material is extruded to form a layer in accordance with the CAD file ²⁰. This method was used to fabricate piezo-electric components using a ceramic/thermoplastic feed-stock ²¹.

These additive techniques have different advantages and limitations (Table1)²² but the main ones are delamination between layers, limited accuracy (material extrusion) and the presence of surface defects on the finished object such as high roughness (powder bed fusion, binder jetting).

Photopolymerization, which refers to stereolithography (SLA), is the most widely used technique. Taking inspiration from the polymer industry and the system developed by Hull in 1986 ²³ and then commercialized by 3D Systems Inc. in 1988, stereolithography was adapted for the fabrication of three-dimensional ceramic parts in the mid-1990s ^{2, 24}. Compared to the other AM technologies, stereolithography and microstereolithography techniques, which will be detailed in the following subsection, meet the challenge to directly build dense ceramic parts with a complex shape and good dimensional accuracy, surface finishing and mechanical properties (Table 1) ²².

II. Photopolymerization: Stereolithography and microstereolithography

(1) Principle of stereolithography

Stereolithography (SLA) consists in building a threedimensional object, layer-by-layer, by selectively curing the surface of a photopolymer with an UV laser beam controlled by a computer (Fig. 2a). Initially developed for polymer parts ^{23, 25}, this process was then extended to ceramics by dispersing ceramic particles in a curable resin ^{2, 24}. The preparation of these reactive suspensions is described in subsection II(3).

3D AM techniques	Tolerance	Advantages	Limitations
Material extrusion	1 mm	 Ease of support removal Good mechanical properties No material waste 	 Precision limited by the filament diameter (about 1 mm)
Material jetting	0.05 mm	 High accuracy Good surface finishing Multimaterial process 	 Cost of the ink Limited to thin layers Limited lifetime of the water based objects
Binder jetting	0.05 to 0.1 mm	Wide variety of materialsSimple technology	 High roughness of the surface Expensive technology Poor mechanical properties Use of toxic organic binders
Sheet lamination	0.1 mm	 High production rates possible Wide variety of materials Low costs No need of support 	 Low vertical accuracy Poor surface finishing Difficulties to produce hollow parts
Vat photopolymeriza- tion	0.01 to 0.1 mm	 Complex designs Good surface finishing Good mechanical properties High accuracy 	 Expensive photosensitive resins Cleaning step necessary Control of the vertical accuracy
Selective laser sintering powder bed fusion	0.2 to 0.5 mm	 High production rates possible Complex designs Low costs Good surface finishing 	 High roughness of the surface Poor mechanical properties Limited to materials which absorb IR light

Table 1: Tolerance, advantages and limitations of AM techniques ²².



Fig. 2: Building sequence of a dense ceramic three-dimensional part with stereolithography (a) or with microstereolithography (b) (picture after 3DCeram).

The object to be built is first simulated using CAD software. The three-dimensional part is then faceted during the conversion of the file into a standard STL format. This STL file is loaded in the automated system that controls the SLA equipment. According to the required resolution and taking into account the reactivity of the ceramic-powder-loaded suspension, the operator determines the thickness of each layer. The control unit then slices the threedimensional object into a series of two-dimensional crosssectional layers. These layers can be from 0.020 mm up to 0.5 mm thick.

The first layer is then deposited. The UV laser beam is focused on the surface of the reactive system. The polymerization of a two-dimensional section is achieved by laser scanning the surface with a galvanometric head (Fig. 2a), allowing precise curing in accordance with the STL file. Polymerization must be slightly deeper than one layer thickness in order to ensure good inter-layer cohesion. Then, the part moves down a layer thickness and a subsequent layer of the reactive suspension is deposited and polymerized according to the next cross-sectional pattern. The process is then repeated until the full three-dimensional object is completed.

The post-processing steps consist in cleaning the consolidated object to remove the excess reactive suspension. The green body is then debinded to remove the organic phase and sintered to finally obtain a dense ceramic part. SLA makes it possible to obtain a good finish with no visible steps on vertical edges owing to the accuracy of the laser beam and on oblique surfaces owing to the low layer thickness (i.e. $20 \,\mu$ m) and the smoothing effect of the sintering using small particle size suspensions.

The density of energy $E_i(J \cdot m^{-2})$ delivered by the laser beam is related to the following parameters: the spot size of the beam ω_0 (m), the power of the laser P_0 (W) and the scanning speed v_s (m·s⁻¹), based on Equation (1):

$$E_{i} = \frac{2P_{0}}{\pi\omega_{0}v_{S}}$$
(1)

Depending on the composition of the reactive suspension, the laser energy must at least reach the critical threshold of exposure (or critical energy of polymerization) to ensure the polymerization of the system. Two parameters must be controlled to ensure good dimensional accuracy and good repeatability of the SLA construction: the cured depth (C_d) and the cured line width (L_p). Several studies ^{26–30} have shown a correlation between the polymerization (E_C), according to the classical absorption Beer-Lambert Law (Eq. 2):

$$C_{d} = D_{P} ln \left(\frac{E_{i}}{E_{c}}\right)$$
⁽²⁾

where D_p is the beam penetration depth or sensitivity. D_p is a characteristic of the system (which depends on the suspension properties: ceramic particle size, volume fraction, refractive index...). D_p illustrates the divergence from the unloaded system.

The cured width is less easy to predict. This parameter takes into account scattering phenomena that control both the cure depth and the dimensional resolution (cure width). There are only few studies that propose an empirical behaviour law ^{28,29}.

(2) Microstereolithography

The microstereolithography (μ SLA) process is derived from SLA. As in the SLA system, three-dimensional fabrication is performed layer-by-layer based on polymerization of a photosensitive system. There are two types of μ SLA: scanning μ SLA and integral μ SLA. The difference between the two techniques lies in the type of insolation of the layers. In the case of the scanning μ SLA, a laser scans the surface of the reactive system, as for the SLA process. The accuracy of this method is derived from a highly focused beam ^{31,32}. But the use of such a method significantly increases the manufacturing time.

With the integral μ SLA method, the complete surface that must be polymerized is integrally irradiated by UV light selectively reflected by a dynamic mask and focalized through an optical system ³² (Fig. 2b).The rapidity and the

high accuracy of this technique are derived from the use of a digital micro-mirror device (DMD). The device used at SPCTS (Fig. 3) is equipped with a matrix of 1024×768 micro-mirrors measuring $14 \times 14 \,\mu m^2$. Each mirror can be rotated from $\pm 12^{\circ}$ along its diagonal (Fig. 4) ³³. The DMD is used as the dynamic mask. For each layer, the micromirrors of the DMD are deflected according to a black and white 2D bitmap file of 1024×768 pixels obtained by cutting the CAD file of the object to be built. A pixel "on" (black) gives rise to an orientation of the corresponding micro-mirror towards the working surface, and a pixel "off" (white) induces a tilt of the micro-mirror outwards (Fig. 4). Each layer is insolated in one step, ensuring a faster shaping than with the scanning method and a homogeneous distribution of energy. In the integral µSLA method, the required density of energy is adjusted with the exposure time.



Fig. 3: Photography (a) and schematic representation (b) of the microstereolithography developed at SPCTS laboratory.

(3) Reactive suspensions for SLA and μ SLA and photopolymerization process

The reactive suspension for SLA and μ SLA consists in ceramic particles dispersed in a reactive monomers/ oligomers resin in which a photoinitiator is dissolved. The rheology of these suspensions has to be adjusted to the process and optimized to obtain reliable ceramic parts.



Fig.4: Principle of insulation of a cross-sectional pattern using a Digital Micro-mirror Device (DMD, Texas Instruments) in the μ SLA process.

(a) **Preparation of the reactive suspensions**

A SLA or μ SLA UV reactive system is commonly composed of a reactive resin (oligomers/monomers mixture), a dispersant, a photoinitiator and a ceramic powder (alumina, zirconia, hydroxyapatite...). The ceramic powder is dispersed with the help of a dispersant in the organic medium composed of the mixture of monomer(s) and oligomer(s) in which the photoinitiator is dissolved.

The physical and chemical properties of the monomers and oligomers are of prime importance for the polymerization process, so these components must be chosen carefully. The final reactive system must present the following properties ^{2, 34}: i) it has to be highly reactive under the UV laser beam; ii) the rheology of the reactive suspension must be adapted to the spreading of the thin layers (down to 10 µm), iii) the powder loading must be larger than 50 vol% to avoid deformation, crack formation and excessive shrinkage during debinding and sintering of the shaped part ^{2,24}; and finally, iv) the green polymerized part must have sufficient mechanical strength to be handled. The monomers and oligomers are therefore chosen according to their viscosity and their functionality, this last property being directly linked to the mechanical strength of the polymer. The main difficulty here is to find the best compromise between high functionality and low viscosity. The more the monomer or oligomer is functional, the more it is viscous, but the final network created after polymerization shows a higher mechanical strength. The commonly used oligomers and monomers are given in Fig. 5³⁴. The low-viscosity acrylates are the most commonly employed oligomers in the SLA technique.

(b) Polymerization process and analysis

Polymerization is a process during which small molecules of monomers/oligomers are linked together to form larger molecules of polymers. The SLA and μ SLA are mainly based on radical polymerization of the organic system, which means that the system needs a catalyst (free radicals coming from the photoinitiator in this case) to trigger polymerization ³. The radical photopolymerization comprises three important steps: initiation, propagation and termination.



Fig. 5: Main properties of various acrylate monomers and oligomers commonly used in the SLA and μ SLA systems ³⁴.

The UV light delivers a certain quantity of photons, which are absorbed by the photoinitiator (PI). The photoinitiator is then decomposed in two free radicals R_1^* and R_2^* (Eq. 3):

$$\mathrm{PI} + \mathrm{h}\nu \to \mathrm{PI}^* \to \mathrm{R}_1^* + \mathrm{R}_2^* \tag{3}$$

where hv is the photon energy.

These free radicals are then transferred from the photoinitiator molecule to the monomer unit (M), (Eq. 4).

$$R^* + M \to RM^* \tag{4}$$

Once the chain has been initiated, propagation occurs. At this stage, the monomers or oligomers units are added on the growing polymer chain (Eq. 5) until termination occurs by recombination (Eq. 6) or disproportionation (Eq. 7).

$$\mathrm{RM}_{\mathrm{n}}^* + \to \mathrm{RM}_{\mathrm{n+1}}^* \tag{5}$$

$$RM_n^* + R'M_m^* \to RM_nM_mR' \tag{6}$$

$$RM_n^* + R'M_m^* \to RM_n + R'M_m \tag{7}$$

$$V_{P} = R_{P}[RM]_{n}^{\circ}] \cdot [M]$$
(8)

The variation of the monomer concentration is expressed by the rate of propagation (V_P) (Eq. 8), where R_P is the reaction rate for polymerization rate.

The conversion rate (C_P) of a monomer/oligomer during polymerization can be determined from Real-Time Infrared Spectroscopy (RTIR) ^{27, 35, 36}. The evolution of chemical bonds, from the oligomer to the polymer, is followed by means of IR spectroscopy on a sample exposed to UV insulation. For instance, the double C=C bond vibrations (stretching) of an acrylate at 1600–1650 cm⁻¹ decrease with exposure time (Fig. 6). This results from the conversion of the double C=C bond into a single bond during the polymerization reaction. At the same time, the main peak in the 1750 cm⁻¹ region, corresponding to the carbon-oxygen double bond stretching, remains unchanged, making it a good reference point. Then, the conversion rate (C_R can be calculated using the following formula (Eq. 9):

$$C_{R}(t) = \frac{\frac{A_{0}^{1620}}{A_{0}^{1750}} - \frac{A_{t}^{1620}}{A_{t}^{1750}}}{\frac{A_{t}^{1620}}{A_{t}^{1750}}}$$
(9)

where A_0 is the initial absorbance of the suspension without any UV exposure, and A_t is the absorbance at a time t of the UV exposure. The area A_t^{1620} corresponds to the area measured in the 1600 – 1650 cm⁻¹ region. The area A_t^{1750} corresponds to the area measured in the 1650 – 1800 cm⁻¹ region.



Fig.6: FTIR scans of a polymerization monitoring experiment (a); typical conversion rate (C_r) and polymerization rate (R_p) vs time (b) for an acrylate reactive system containing alumina powder (50 vol%).

It is possible to combine this region with the monitoring of the 810 cm^{-1} region or the $1400 - 1430 \text{ cm}^{-1}$ region, which are also characteristic of the carbon-carbon double bond stretching, allowing higher precision in the calculation. During the UV curing, the propagation speed increases to reach its maximum in only a few seconds and the conversion is not complete (Fig. 6) ^{26, 36}.

II. Results/Applications

SLA and μ SLA technologies are increasingly used as full production tools, to fabricate useful ceramic parts for a

wide range of new applications. Some examples of complex ceramic parts shaped by SLA or μ SLA for three different fields of interest, i.e. information and communications, health and jewellery, are described in this section.

(1) Information and Communications Technologies (ICT)

The complex three-dimensional devices used in the field of ICT mainly require high dimensional accuracy to reach the desired performance. The ability of SLA and μ SLA techniques to fabricate complex shapes with a high dimensional accuracy makes it possible to develop new ICT devices and to open up new perspectives in the conception of resonant devices and filters. Photonic crystals ^{37, 38}, dielectric resonators ³⁹ or filters ⁴⁰ are examples of ICT devices processed thanks to SLA.

Photonic (more generally electromagnetic) bandgap crystals are artificial electromagnetic crystals able to reflect certain light or microwave wavelengths depending on their lattice spacing and on the material used. By manipulating the structure design and its periodicity, it is possible to control the bandgap, i.e. the wavelength bands that can propagate through the crystal, the other bands being reflected by such a crystal. The most common crystals are reported to have a woodpile ^{37, 38} or a diamond structural arrangement (Fig. 7)³⁸. These structures are highly complex and can even be impossible to shape using any traditional routes. The design of the three-dimensional Electromagnetic Band Gap (3D EBG) built by Delhote et al. (Fig. 8a) 37 is a woodpile-type photonic crystal (periodic structure) in which a structural defect is placed, acting as a waveguide. The goal here is to build the full device as a single ceramic part to improve the accuracy of the waveguide position in the woodpile and to optimize the properties of the complete device. A reflexion parameter S_{11} under -10 dB shows that the circuit is adapted to the frequency of work, and a transmission parameter S₂₁ close to 0 dB shows a maximum of transmission (Fig. 8b). When both parameters are reached, the waveguide is effectively capable of guiding EM waves (around 25 GHz in this example).



Fig. 7: Three-dimensional models of unit cells in the photonic crystals with a diamond structure (a) and an inverse diamond structure (b) ³⁸.

Ceramic bandpass filters with a high unloaded quality factor ($Q \cong 3000$) are based on an optimized arrangement

a)





Experimental (meas.) - Simulated (sim.)

Fig. 8 : Electromagnetic BandGap antenna fabricated with SLA (zirconia ceramic) (a); Experimental (meas.) and simulated (sim.) reflexion (S₁₁) and transmission (S₂₁) parameters (b) ³⁷.

3D pyramidal and collective Ku bandpass alumina filters are another example of ICT applications. These filters are used for space applications so they must have high dimensional accuracy, remain flat, be manufactured with highperformance RF material (high-purity alumina) and require coplanar input/output accesses to be connected into a full device with metal wire bondings. All these requirements are achieved thanks to stereolithography tech-



Fig. 9 : Dielectric resonator in its cavity fabricated with SLA (alumina ceramic) (a); simulated and experimental performances of the structure (b) ⁴⁰.

(2) Health

Bone tissue has the ability to regenerate itself. Nevertheless when the bone defect is too large, induced by traumatic injuries, tumour resection or infection, the natural bone healing process can fail and it is necessary to use grafts. In this situation the best solution is the autologous bone graft because it combines all the required properties: osteoconduction (scaffold), osteoinduction (growth factors) and osteogenesis (osteoprogenitor cells). However, these grafts have many disadvantages ⁴¹. The bone graft harvesting can be an additional complicating factor at the level of the donor site, including pain, haematoma, infection, nerve injury. Furthermore, the resorption rate of these natural implants is sometimes too high. Finally, the limited amount of autologous bone grafts makes the filling of large bone defects impossible. The limits of bone grafts favoured the emergence of totally synthetic biomaterials. Polymers cannot be considered for bone substitutes because of their lack of osteoconductive properties and their tendency to induce a high inflammatory response. Some metals, like titanium, have been used as biomaterials, but cannot be envisaged for bone substitution because of their thermal conductivity and their heavy weight. The best adapted biomaterials for bone substitution are calcium phosphate ceramics because of their excellent biocompatibility and their faculty to conduct bone onto their surface. It is well

known that an interconnected macroporosity (around $300-600 \mu m$ with interconnections of $50-100 \mu m$) is required for bone regrowth within the implant bulk through its pores network ⁴². Moreover, shapes with concavities have been shown to be suitable for cell migration and proliferation ⁴³. An important goal in bone tissue engineering is thus focused on developing three-dimensional ceramic porous scaffolds with controlled complex architecture. This kind of architectures cannot be shaped by means of conventional methods as they do not permit accurate control of structural parameters.

SLA and µSLA are considered powerful methods to shape such three-dimensional ceramic scaffolds. Particularly, bone graft substitutes made of calcium phosphate hydroxyapatite are processed by means of SLA for specific reconstruction of large and complex craniofacial bone defects. After the patient has been scanned (Fig. 11a), a three-dimensional (3D) file of the future implant, adapted to the defect morphology, is generated by means of computer-aided design (Fig. 11b). This 3D CAD file is used as previously described (Fig. 2) to shape the scaffold layer by layer. The green body, consisting of a composite made of polymerized resin and hydroxyapatite, is further debinded and consolidated by sintering (Fig. 11c). The bone substitute is then implanted, after sterilization (Fig. 11d). The adaptation of the prosthesis to the bone defect is confirmed by the absence of depression between the prosthesis and the surrounding living bone, after implantation. This technique allows processing, with sufficient accuracy, of the three-dimensional porous architecture (macropores of $300-550 \mu m$) required in the peripheral area of the implant for further bone ingrowth and long-term attachment of the implant to the surrounding bone tissues as well as the holes necessary for its fixation during surgery (Fig. 11e) ⁴⁴. Tailormade cranial substitutes are currently produced and marketed by the 3DCeram company and implanted by the Neurosurgery and Maxillofacial Surgery Departments of Limoges University Hospital Centre ⁴⁴. Such porous ceramic scaffolds with complex shapes, for the repair of bone defects larger than 25 cm^2 , are produced within about two weeks and the manufacturing cost of an implant is around $10\,000 \in$.



Fig. 11: Main processing steps of a cranial prosthesis (calcium phosphate ceramic): patient scanning (a), simulation of the three-dimensional file by CAD (b), shaping by SLA and sintering (c), implantation (d), porous edges of the implant (e) (3DCeram, Limoges, France).



Fig. 10: Pyramidal vias integrated at the bottom of a resonator (a); Final 4-pole filter integrating the pyramidal resonators and vias (b); Views of the filters (alumina ceramic) before and after metallization with copper and gold and then etched with a YAG laser (c); Experimental (retro.) and simulated (sim.) reflexion (S₁₁) and transmission (S₂₁) parameters (d) ³⁷.

(3) Jewellery

The luxury field requires high precision in the small dimensional details of the products and a high standard of quality. Most of the items are a unique piece of art, created by designers. The accuracy and the surface finishing achieved with stereolithography techniques allow the processing of such parts with a high quality that meets the standards of this luxury industry. As there are no constraints on the design, the creators can imagine a unique piece of jewellery such as the ring shown in Fig. 12. The ceramics mainly used to build these parts are alumina and zirconia (coloured or not).



Fig. 12: Luxury ceramic part shaped by SLA (3DCeram, Limoges, France).

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