Ceramic Fabrication Using Mask-Image-Projection-based Stereolithography Integrated with Tape-casting

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Abstract

Ceramic components with complex geometry are difficult to fabricate. Layer-based additive manufacturing processes such as ceramic-suspension-based stereolithography (SL) provide a direct way of fabricating ceramic components from computer-aided design (CAD) models. In such a SL process, fine ceramic powders are mixed with liquid photocurable resin into ceramic suspension. The suspension-based slurry is then used in the SL process to fabricate green parts with desired shapes. A sintering process is further required to convert the green parts into dense ceramic components. In this paper, several key challenges of the ceramic-suspension-based SL process are discussed including the recoating and curing ceramic suspension with high solid loading. A novel *Mask-Image-Projection-based Stereolithography* (MIP-SL) process by integrating ceramic tape-casting and bottom-up projection methods is presented for fabricating dense ceramic components from CAD models. Various approaches to increase the solid loading in green parts are discussed including suspension preparation, image projection, layer recoating and separation. A prototype system based on the presented ceramics fabrication process has been developed. Test cases of different types of ceramics are presented to demonstrate the effectiveness of the presented fabrication method. The post-processing of green parts to convert them into dense ceramic components is also discussed with some sintering results presented.

Keywords: Additive manufacturing, stereolithography, ceramic suspension, recoating, viscosity, tape casting.

1 Introduction

Additive manufacturing (AM) processes can directly fabricate three-dimensional (3D) computer-aided design (CAD) models by selectively accumulating building materials. The benefits of AM

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processes include fast building speed, no need for part-specific tools and fixtures, and the capability of building components with complex geometry. However, current AM processes also have limitations especially the material selections are limited. Most of current AM processes focus on plastics and metals. Another type of engineering materials, ceramics and ceramics-based composites, is severely limited for current AM processes.

To overcome such material limitations, researchers have studied AM processes using high-performance ceramic powders. A developed method based on Selective Laser Sintering (SLS) is to use high energy laser beam to locally sinter ceramic particles such that they will bond with each other. However, due to the high sintering temperature of ceramics, low melting point media such as polymer powder is usually added with ceramic powders. As shown in Figure 1a, the low-melting point particles serve to bind ceramic particles together in the SLS process. Finally some post-processing procedures are performed to burn out the added binder and to fuse ceramic particles.

Figure 1: Different methods of bonding ceramic powders in additive manufacturing

Due to the good properties of stereolithography (SL) such as high accuracy and good surface finish, efforts on applying SL in ceramics fabrication have been made. In such an AM process photosensitive resin is used to bind ceramic particles together (refer to Figure 1b). That is, liquid resin is mixed in ceramic suspension and selectively solidified due to controlled light-induced photopolymerization. Consequently, green parts with different shapes can be fabricated using ceramic suspension that is a mixture of ceramic powders and photosensitive resin. Post-processing of the fabricated green parts is needed to burn out the organics in photosensitive resin and to fuse ceramic particles together in order to get dense ceramic components. In the section, we will first review the previous work on the ceramic suspension based SL processes; the main challenges of the ceramics SL process are discussed followed by the main contributions of the paper.

3.1 Overview of ceramic suspension based additive manufacturing processes

The main AM processes that have been used to fabricate ceramic components from ceramic suspension include (1) direct inkjet based printing, (2) extrusion-based direct-write technique, and (3) light exposure based stereolithography.

The direct inkjet printing process (Lee, 2004; Noguera, 2005) is a simple and potentially fast approach for building ceramic components with complex shapes. In the process, ceramic powders are mixed with liquid dispersant into slurry. The slurry is then jetted through small nozzles to form micro-droplets that can accumulate into 3D structures. However, the strict requirements on the viscosity of ceramic slurry for jet-ability limit the solid loading that can be added in the ceramic suspension.

The extrusion-based direct-write technique (e.g. Sun, 2010) uses a nozzle system to extrude and deposit ceramic slurries or pastes. After the green part is built by the extrusion and deposition process, the built structure is debinded and sintered in a furnace. Although the nozzle deposition process enables the fabrication of complex shapes using slurry with high solid loading, the process has disadvantages such as low fabrication speed and low surface quality.

The Stereolithography Apparatuses (SLA) process has been investigated for fabricating ceramic components. In the SLA process, a focused UV laser is used to selectively solidify ceramic suspension. Compared with the extrusion-based Fused Deposition of Ceramics (FDC) process, the laser-based

SLA process has a faster speed with better accuracy and surface finish. However, since powder suspension is used in the ceramics SLA process, recoating viscous ceramic slurry into uniform thin layers has been a challenging issue.

In previous research on applying the SLA process to ceramic suspension fabrication, the recoating of highly viscous slurry has been extensively studied. Griffith and Halloran (1996) discussed the limitation of resin viscosity in SLA in order for slurry to achieve proper flow-ability during the layer recoating process. To ensure ceramic suspension to have a viscosity value less than 3000 mPa·S, low-viscosity UV-curable liquid resins need to be selected; dispersants to reduce slurry viscosity may be added; in addition, the solid loading in suspension cannot be high, usually less than 0.5-0.65 solid volume fraction. Jiang *et al.* (2000) used a conventional μ SL apparatus to fabricate Lead Zirconate Titanate (PZT) thick films on silicon substrate. In their setup, uniform PZT suspension layers are spread by controlling the distance between a precision blade and the substrate. A similar recoating method is used in (Dufaud, 2002) to spread ceramic slurry into uniform layers. Instead of using a blade, Dufaud *et al.* (2003) presented a new recoating system, in which a nozzle injects a controlled nitrogen flow to spread the ceramics suspension. Based on the new recoating system, it was discussed simple green parts with 80wt% of ceramic powder and more elaborated rods with 50wt% of ceramic powder can be fabricated, respectively.

The SL process can use other imaging approaches instead of a laser. The Mask-Image-Projection-based Stereolithography (MIP-SL) is an AM process that also uses photopolymerization to fabricate 3D shapes. However, in the MIP-SL process, a Digital Micro-mirror Device (DMD) is used to dynamically project the mask image of sliced layers onto the surface of photosensitive resin. Hence, the shape of a whole thin layer can be solidified simultaneously.

Many researchers have used the MIP-SL process to fabricate ceramic parts as well. Ventura *et al.* (2000) presented the fabrication of silicon nitride ceramic components using the MIP-SL process. Similar to the laser-based SLA process, a doctor blade is used to coat uniform thin layers. Then the mask image of the part cross section is projected to cure the related layer. Cheverton *et al.* (2012) present a method by dispensing the slurry through a syringe that was connected to a pneumatic pump. The spread slurry is then recoated by using a doctor blade, which is cleaned with a sponge to remove the residual slurry on it after each layer is recoated.

Chabok, *et al.* (2012) investigated the fabrication of PZT ceramics using the MIP-SL process. A novel two-channel bottom-up projection based system was developed to achieve the separation of cured layers from the slurry tank. Since mask images are projected on the bottom of a transparent vat, the layer recoating is achieved by moving the platform to form a gap between the vat bottom and the previously cured layers. Similarly, Seol *et al.* (2013) use a bottom-up projection-based μ SL system to fabricate scaffold structures from commercial HA (hydroxyapatite: $\text{Ca}_{10}(\text{PO}_4)_6(\text{OH})_2$) and TCP (tricalcium phosphate: $\text{Ca}_3(\text{PO}_4)_2$) powder.

3.2 Main challenges in ceramics SL process

Two main challenges exist in the ceramic suspension based SL process. One main challenge is the layer recoating, in which a uniform thin layer is formed within a reasonable time. Compared with liquid resins that are commonly used, the slurry made by mixing ceramic powders and liquid resin has an increased viscosity. In the SLA process (Jacobs, 1992), light is projected onto a free slurry surface and new layers are solidified on the top of previously cured layers. As shown in Figure 2a, the top-down projection based method requires a tank filled with slurry. After a layer is built, the platform moves down in the Z axis for one layer thickness δ (e.g. $\sim 100\mu\text{m}$). A blade is moved across the top free surface of the slurry to form a new layer. In order to form uniform layers, the viscosity of the slurry cannot be high; otherwise, it is increasingly difficult to recoat thin layers. In addition, ultrathin layers such as $10\mu\text{m}$ layer thickness cannot be achieved for viscous slurry. Another drawback of the top-down projection based method is the volume of the slurry in the tank must be large to allow layer

recoating at different part heights. The particles in the slurry tend to become aggregated after the well-mixed ceramic suspension has been stored in the tank for a while.

Instead of using a slurry-filled tank, another recoating approach is to directly deposit slurry on top of the previously built layers as shown in Figure 2b. The recoating approach eliminates the needs of large amount of slurry, and avoids particle aggregation in the suspension. However, due to the surface tension of the slurry, the recoated layers by a blade tend to have defects, which will adversely affect the surface finish of green parts. A test example based on the recoating approach is shown in Figure 2b.

In addition to layer recoating, another main challenge in the ceramic suspension based SL process is the reduced cure depth. That is, when light travels through ceramic slurry, the ceramic particles will block and scatter the incoming light. Hence, the cure depth will be significantly reduced. Accordingly, a smaller layer thickness is needed to accommodate the reduced cure depth. However, it will impose difficulty in recoating such ultrathin layers.

In summary, the two main challenges of the ceramics SL processes are listed as follows.

(1) *The limitation in recoating slurry with high viscosity.* Higher solid loading in ceramic suspension will lead to slurry with larger viscosity. The use of diluents and a heating system may reduce the slurry's viscosity to certain extent (Jang, 2000). However, the addition of diluents may lead to issues such as the large shrinkage and fragility of the structures (Melchels, 2009). Increasing the temperatures of ceramic slurry will require an additional heating system; in addition, the temperature increase has a limited range since resin may be cured by increased temperature as well. Hence the resulting viscosity may still be too high to ensure a good layer recoating (Hinczewski, 1998).

(2) *The limitation in recoating slurry in ultrathin layers.* The SLA process based on the top down projection based method usually has a layer thickness around 100 μm (Griffith, 1996). For ceramics that may have a smaller cure depth (e.g. PZT), a layer thickness as small as 10 μm may be required to ensure sufficient overcure between layers.

Figure 2: Two recoating processes for the top-down projection method.

3.3 Contributions of the paper

A bottom-up projection based MIP-SL process by integrating ceramic tape-casting and a two-channel sliding design has been developed. In our method, an integrated tape-casting system is used to recoat thick layers on a transparent glass substrate; uniform thin layers are then recoated by moving the platform to form a desired gap between the previously cured layers and the glass substrate. After the layer recoating, mask images are projected upwards onto the bottom of the substrate. The newly cured layer is separated from the substrate using a two-channel sliding design. A comparison between different ceramic suspension based SL processes is shown in Table 1. Compared with other processes,

our method can achieve a thin recoating layer (as small as $10\mu\text{m}$). By using the bottom-up projection approach, it also removes the need for a large amount of slurry. In addition, a higher shear rate in our tape-casting system is able to reduce the viscosity of suspension during the recoating due to the shear thinning behavior of ceramic/resin suspension (Chartier, 1999). Hence our ceramics SL process can fabricate green parts using slurries that have significantly higher solid loadings.

	SLA (Griffith, 1996; Dufaud, 2002)	MIP-SL (Chabok, 2012)	Our method
Energy source	Laser	Mask Image	Mask Image
Light direction	Top-down	Bottom-up	Bottom-up
Required amount of Material	Full tank	Height < 10mm	Height < 2mm
Layer thickness	50-100 μm	<10 μm	<10 μm
Recoating shear rate	Low	Low	High
Diluent Solution	Yes	Yes	No or little

Table 1. A comparison between different ceramic-suspension-based SL processes

The remainder of the paper is organized as follows. The layer recoating process based on the tape-casting-integrated MIP-SL process is presented in Section 2. Ceramic slurry preparation and its curing characteristics are discussed in Section 3. Section 4 presents the prototype system of the developed ceramics SL process and some of our test cases. The post-processing of green parts for fabricating dense ceramic components is discussed in Section 5. Finally conclusion and future work are drawn in Section 6.

2 Green Part Fabrication Using Tape-casting Integrated MIP-SL

High solid loadings in ceramic suspension are desired such that good physical properties can be obtained after the fabricated green parts are sintered. However, as discussed in Section 1, recoating ceramic suspension with high viscosity is difficult in the top-down projection based SLA process. To address the challenges, we develop a tape-casting-integrated MIP-SL process based on the bottom-up projection approach, which can build ceramic green parts using slurries with high solid loadings.

2.1 Bottom-up projection for MIP-SL

Different from the top-down projection based approach as shown in Figure 2, the bottom-up projection based MIP-SL process is shown in Figure 3. Mask images are projected through a transparent resin tank to cure layers that are hung upside-down on the building platform. In addition,

Figure 3: MIP-SL process using the bottom-up projection method.

the bottom of the resin tank is coated with materials such as PDMS to facilitate the separation of newly cured layers (Zhou, 2013). The benefits of the bottom-up projection based approach include:

(1) Only a small amount of building material is need. It is not required to have a tank filled with slurry during the fabrication process. Hence the problem of slurry sitting in the tank for a long time can be avoided.

(2) The recoating of ultrathin layers is enabled. In the bottom-up projection based system, a new layer is sandwiched between previously cured layers and the bottom of the tank. Hence its thickness can be accurately controlled by adjusting the height of the building platform.

2.2 Tape-casting integrated with the bottom-up projection based MIP-SL

Tape casting is a widely used ceramic manufacturing process that can produce thin ceramic tapes from various types of slurries. Its capability of coating uniform thin layers presents an approach for recoating ceramic/resin slurry in the ceramics SL process. Figure 4 shows the main components of the developed tape-casting-integrated MIP-SL process. The figure shows the moment when an initial layer is cured and has not been detached yet. The developed system consists of a Z stage, a DMD based projection system, and a tape casting module. The tape casting module is made up of a film collector and a linear guide to move it in the X axis. The film collector is mainly an embedded glass sheet with a coated PDMS layer.

Figure 4: Green part fabrication using tape casting integrated MIP-SL.

In our previous research on multi-material fabrication (Zhou, 2013), it is shown the separation force is considerably large when the Z stage is directly pulled up even with the coated PDMS film on the film collector. In addition, the separation force will significantly increase when the resin viscosity is increased. Hence, for viscous ceramic slurry that is used in the ceramics SL process, the separation force will be large. If such a separation force is larger than the bonding force between the newly cured layer and the previously cured layers, the newly cured layer will be detached from the part and the building process will fail. To facilitate the layer separation, a sliding mechanism based on a two-channel design is presented in (Zhou, 2013). Compared to the separation force during a direct pulling-up, the shearing force during a sliding motion along the X axis is much smaller. The two-channel design as discussed in (Zhou, 2013) is also used in our tape-casting-integrated MIP-SL process.

As shown in Figure 5, the film collector can be moved along the X-axis, and the Z stage can be moved along the Z-axis. The height of a doctor blade is set to be δ_{Blade} . Note that δ_{Blade} is usually much larger than the layer thickness δ (i.e. $\delta_{Blade} > \delta$). The film collector is divided into two channels, one

has the PDMS coating and another one has not. The mask images controlled by a DMD are only projected onto the channel that has the PDMS coating.

After a layer is cured, the Z stage first moves up for a small distance ($d_{release}$) to release the stress in the cured layer generated in the polymerization process. Right after the lift-up, the film collector slides from left to right with a speed of V_r for a distance d_{feed} . As discussed in (Zhou, 2013), the force in this sliding movement is relatively small since a thin oxygen-aided inhibition layer ($\sim 2.5 \mu\text{m}$) is formed near the PDMS film, which can provide a non-polymerized lubricating layer for easy sliding. As soon as the cured layer slides to the channel that has no PDMS, the vacuum between the cured layers and the film has been broken. The built layers thus can be detached from the film collector. The peak separation force based on the sliding mechanism is only 4-5% of that based on the direct pulling-up approach (Zhou, 2013).

The film collector moves all the way to the right under the dispenser to add new slurry. Before the film collector moves back, the building platform is moved up for a distance d_{lift} (0.5~1mm) to allow the slurry that is spread by the blade to be conveyed underneath the built layers. After the film collector returns with a speed of V_r , the Z stage moves the building platform down for a distance $\delta - d_{release} - d_{lift}$. Thus a gap of one layer thickness is left above the PDMS film. Hence, based on a thick layer that is formed by the tape casting module (i.e. δ_{blade}), the designed motion of the platform can further form a thinner layer of slurry (i.e. δ). Even for rather viscous slurry, our system can achieve a layer thickness δ as small as $10\mu\text{m}$. Such ultrathin layers are difficult to be formed if only the doctor-blade-based tape casting process is used.

2.3 Main process parameters in layer recoating

The main process parameters in the layer recoating process are discussed as follows.

(1) Blade gap δ_{blade}

A small amount of slurry is dispensed behind the doctor blade for each layer. Since the pressure in the dispensed slurry can be ignored, the blade recoating procedure can be modeled with a plane Couette flow pattern (Chou, 1987). As shown in Figure 6, the bottom plate moves at a constant speed of V_r relative to the blade.

The boundary conditions follow:

$$\begin{aligned} u_x &= v_r, \text{ at } y = 0; \\ u_x &= 0, \text{ at } y = \delta_{blade} \end{aligned} \quad (1)$$

By solving the Navier-Stokes equations under the given boundary conditions, a simplified equation of the thickness δ' of the wet recoated layer can be derived as:

$$\delta' = \frac{\eta}{2\rho v_r} \delta_{blade} \quad (2)$$

Figure 5: Process planning for the tape casting integrated MIP-SL process.

Figure 6: The velocity profile in the blade recoating.

where ρ is the slurry density and ρ' is the density of the newly formed layer. To ensure layer bonding, δ' must satisfy $\delta' \geq \alpha \delta$, where α is a safety factor to ensure neighboring layers will be bonded ($\alpha > 1$).

Hence the inequation for blade gap δ_{Blade} must hold:

$$\delta_{Blade} \geq \frac{2\rho\delta^2}{\rho'} \quad (3)$$

(2) Recoating speed V_r

Shear rate $\dot{\gamma}$ is calculated by recoating speed V_r and blade gap δ_{Blade} at $\dot{\gamma} = \frac{V_r}{\delta_{Blade}}$. Due to the shear thinning behavior of ceramic suspension, a higher shear rate will lead to a lower viscosity of the slurry when the slurry passes the blade. Thus the sedimentation of ceramic particles in the recoated layer can be avoided, and a good homogeneity of the fabricated green parts can be achieved. With the same blade gap, a higher recoating speed V_r will generate a bigger shear rate $\dot{\gamma}$, and accordingly a smaller slurry viscosity.

(3) Sliding speed V_s

After a layer is cured, the platform goes up for a small distance from the PDMS. Then the film collector moves in the X axis with a speed V_s to detach the newly cured layer from the PDMS film. Suppose a cylindrical shape is being fabricated, whose diameter is d and the current building height is L . As shown in Figure 7, when the part slides from left to right, the portion of the cylinder immersed in the slurry layer will experience a drag force F in the slurry moving direction as the average force q ($q = \frac{F}{\delta'}$).

Based on the drag force equation, we know:

$$F = \frac{1}{2} \rho v_f^2 C_D A \quad (4)$$

where ρ is the mass density of the slurry; C_D is the drag coefficient that is related to Reynolds number Re of the slurry and can be identified by experiments; A is the reference area. In our case, $A = \frac{\pi d \delta'}{2}$.

Substitute Equation (4) into the flexure formula of a cylinder, the maximal normal stress σ can be derived as:

$$\sigma = \frac{8\rho v_f^2 C_D \delta' L}{d^2} < [\sigma] \quad (5)$$

Hence,

$$0 < v_f < \sqrt{\frac{[\sigma] d^2}{8\rho C_D \delta' L}} \quad (6)$$

The material used in our tests has a minimal bending stress $[\sigma] = 65\text{MPa}$.

Figure 7: Drag force during the layer detachment

3 Ceramic Suspension And Its Curing Characteristics

In addition to the difficulty in recoating ceramic slurry, another main challenge in the ceramic suspension based SL process is the reduced curing depth. As mentioned before, ceramic slurry is prepared by mixing ceramic powders with photocurable resin. In the fabrication process, the resin will serve as the binder to bond ceramic powders into given 3D shapes. During the sintering process, cured resin will then be burned out and ceramic particles can grow into each other such that the sintered ceramic part can be dense.

The physical properties of the sintered ceramic parts largely depend on the amount of ceramic powders that are mixed in the slurry. The more powders in the slurry, the denser the sintered ceramic parts will be, consequently the better material properties. However, a higher percentage of ceramic

powders in the mixed slurry will also dramatically decrease the curing sensitivity of the slurry while increase its viscosity. Hence both layer recoating and curing processes would be more difficult.

3.1 Slurry Preparation

In our study, different ceramic powders are tested using the presented ceramic fabrication process. They include Alumina (type CR3, Baikalex, Charlotte, NC), Zirconia (TZ-3YS-E, Tosoh, Tokyo, Japan) and PZT (Piezoelectric Technology Inc., Indianapolis, IN). To remove the agglomeration in the raw powders, the bought ceramic powders are grinded with ethanol and zirconia media (Stain steel beads) in a ball mill (Fritsch GmbH, Idar-Oberstein, Germany) at the room temperature for 24-48 hours. After the mixture is dried at a temperature of 50°C, we premix the grinded powders with photocurable resin (SI500, EnvisionTec Inc., Ferndale, MI) in a mortar based on a designed ratio. The mixture is then milled at 200rpm for another 1-2 hours. The photocurable resin has a viscosity of 0.18Pa•s at 30°C and a density of 1.10g/cm³ at 25°C. Its glass transition temperature is 61°C. The resin is selected in our study due to its excellent photosensitivity. It contains 60-90wt% Methacrylated monomer, 5-10wt% 1,6-Hexanediol acrylate, 5-15wt% Acrylated monomer, 1-2wt% Titanium dioxide and 0.1-1wt% photoinitiator.

Before ball milling, dispersant can be added into the mixture in order to disperse solid particles homogeneously in the liquid resin. Similar to other ceramic SL processes (Dufaud, 2003; Ventura, 2000; Cheverton, 2012; Chabok, 2012), solvent such as IPA can also be added to reduce the slurry viscosity. Due to the integrated tape casting system and two-channel sliding design, less diluent solvent is required in our process. Finally the mixture is degassed in a vacuum chamber (Bel-Art Products, Wayne, NJ) for 30 minutes to remove the air bubbles that may be generated during the ball milling process.

3.2 Curing Characteristics

Due to the high refractive index of ceramic powders when compared to photocurable resin, the cure depth of mixed ceramic slurry is significantly reduced. Table 2 shows the cure depths of three different types of ceramic suspension that are measured using the developed prototype system. A single-layer-curing method is used in measuring the cure depth of ceramic slurry. That is, after the ceramic suspension is tape-casted by a doctor blade, an image of a circle with the diameter of 10mm is projected bottom-up onto the ceramic slurry. After the mask image is projected for 10 seconds, a thin layer of ceramic composite will be solidified. Its thickness can be measured by a micrometer caliper. For high refractive ceramic materials such as PZT, its refractive index can be as high as 2.4. Consequently, the layer thickness during the fabrication process needs to be reduced to 10µm such that the cure depth is larger than the set layer thickness to ensure good bonding between layers.

Type	Cure depth (µm)	d50 (µm)	n _p @ 632.8nm	Density (g/cm ³)	Resin	Cure time (s)
PZT	23.6	5	2.397	7.7	SI500	10
Zirconia	82.0	0.09	2.208	6.05	SI500	10
Alumina	250.6	1.1	1.766	3.95	SI500	10
Pure resin	750.0	NA	1.382-1.441†	1.10	SI500	10

Table 2. Physical properties and cure depths of ceramic powders with 65wt%. Note: †refer to (Griffith, 1996).

The light intensity of our projection system is ~2100W/m². The actual light energy absorbed by ceramic slurry is smaller due to the energy loss when light passing through the PDMS-coated film

collector. In our setup the thicknesses of the glass and the PDMS is ~2.38mm and ~1mm, respectively. The cure depth may be slightly different if their thicknesses are modified.

The relation between cure depth and energy input is defined by the Jacob's equation (Jacobs, 1992):

$$C_d = D_p \ln\left(\frac{E}{E_c}\right) \quad (7)$$

where C_d is the cure depth; E is the energy density of incident light; E_c is the critical energy density, i.e. the minimum energy for the photocurable resin to be solidified; and D_p is the resin sensitivity. The parameter D_p is closely related to the absorption by the photoinitiator and the light absorber (e.g. dye) in the resin, as well as the light scattering by mixed particles (Tomeckova, 2010^a).

According to Griffith and Halloran's scattering equation for ceramic suspension (Tomeckova, 2010^a; Griffith, 1997; Abouliatim, 2009; Tomeckova, 2010^b), D_p can be determined by the following equation:

$$D_p = \frac{3d_{50}^2 \Delta n^2}{8Q} \quad (8)$$

where d_{50} is the average particle size; Δn is the refractive index difference between the ceramic particle (n_p) and the liquid resin (n_0 , i.e. $\Delta n^2 = (n_p - n_0)^2$). Q is the scattering efficiency term, which embodies a complex physics for scattering behavior in a dense system. Empirically it depends on volume fraction ϕ , d_{50} , and the light wavelength λ .

Compared with regular photocurable resins, the cure characteristic of ceramic suspensions is affected by the scattering defined in Equation (8). The cure depth depends on the refractive index difference between the ceramic and the resin, the particle size, and the solid loading of ceramic powders in the suspension. Table 2 shows the measured cure depth of PZT, Alumina and Zirconia with the same solid loadings - 65% weight concentration.

Our experiments show that the cure depth of ceramic slurry is dominated by the refractive index difference Δn . Among the three types of ceramics that are tested, PZT has the largest refractive index, while Alumina has the smallest one. Consequently, the cure depth of PZT is the smallest, while the cure depth of Alumina is the largest. The d_{50} as shown in the table is the size from the vendors' datasheets. The actual particle size will be smaller due to the grinding process.

4. PROTOTYPE SYSTEM AND TEST CASES

A testbed including both hardware and software systems have been built to demonstrate the presented ceramics fabrication process.

Figure 8: A developed ceramics fabrication testbed. (a) A prototype system using the tape casting integrated MIP-SL process; (b) the graphical user interface of the developed process control software system.

The hardware system is shown in Figure 8a. A motorized micro positioning linear stage (Danaher Corporation, Washington, D.C., US) is used to drive the building platform in the Z axis. A clear glass sheet (3/32" or 2.38mm thickness) coated with PDMS (Sylgard 184, Dow Corning) is embedded in a film collector. The film collector moves along a linear guide through four linear ball bearing slide bushings. A belt-pulley mechanism was used to drive the film collector in the X axis. A micrometer adjustable film applicator (MTI Corporation, Richmond, CA) is used to conduct material spreading. Its blade height can be adjusted by a micrometer head with an accuracy of $10\mu\text{m}$. Hence the ceramic suspension layer that is recoated can be well controlled to be larger than the set layer thickness. A hopper is fixed behind the blade to dispense a certain amount of ceramic slurry during each motion cycle. Its slip gate is controlled by a linear actuator (Eastern Air Devices, Dover, NH).

A process control software system has been developed using Microsoft Visual C++. Figure 8b shows the graphical user interface (GUI) of the developed software system. The software system can slice a given CAD model and dynamically output mask images to the designed projection system. The projection image size of the prototype system is designed to be $49.5\text{mm} \times 42.2\text{mm}$. The resolution of the DMD chip (Texas Instrument, Dallas, TX) is 1024×768 . The output light intensity of the projector is $\sim 2100\text{W/m}^2$. The software system can also send motion control commands to a 4-axis motion controller (Dynomotion Inc, Calabasas, CA).

Three types of ceramic powders including Alumina, Zirconia and PZT are used in fabricating test cases. Their properties are shown in Table 2. Three groups of slurry with the same solid loading (65wt%) are made by mixing the related ceramics powders with SI500 resin. The viscosity of the mixed slurry is around $5\sim 250\text{Pa}\cdot\text{s}$ with no diluent added in the suspension.

The flow chart of the building process is shown in Figure 9. The main process parameters that are

Figure 9: Flow chart of the tape-casting-integrated MIP-SL process.

The software system can slice a given CAD model and dynamically output mask images to the designed projection system. The projection image size of the prototype system is designed to be $49.5\text{mm} \times 42.2\text{mm}$. The resolution of the DMD chip (Texas Instrument, Dallas, TX) is 1024×768 . The output light intensity of the projector is $\sim 2100\text{W/m}^2$. The software system can also send motion control commands to a 4-axis motion controller (Dynomotion Inc, Calabasas, CA).

(a)

The flow chart of the building process is shown in Figure 9. The main process parameters that are **Figure10:** Green parts fabricated by the tape-casting-integrated MIP-SL process.

used in the fabrication process are listed in Table 3. A longer curing time is used when building the initial 5-10 layers; for other layers, a shorter curing time is used. Both of them for each type of ceramic powders are given in Table 3.

	Curing time (s)	Layer thickness (μm)	Blade gap δ_{blade} (μm)	Recoating speed V_r (m/s)	Sliding speed V_s (m/s)
Alumina	15/10	50	250	0.05	0.05
Zirconia	25/20	30	150		
PZT	60/30	10	100		

Table 3. Main process parameters used in the fabrication process

Figure 10 shows some of the fabrication results based on the selected process parameters. Figure 10(a) is a PZT ultrasound transducer array with hexagon pillars. The size of the array is $6.5\text{mm} \times 6.5\text{mm} \times 1.0\text{mm}$, and the width of each pillar is 0.85mm ; Figure 10(b) shows USC characters in Zirconia; and Figure 10(c)~(e) show some parts that are made from Alumina powders.

5 Post Processing of Green Parts

The green parts fabricated by the tape-casting-integrated MIP-SL process consist of organic compound (cured resin) and ceramic powders. In this section, we briefly discuss the post processing of the fabricated green parts in order to achieve fully dense ceramic components. The main post processing steps include organic binder burning-out and high-temperature sintering. In the section, a test case of a gear model is used to demonstrate the post-processing procedures. The green part fabricated by the tape-casting-integrated MIP-SL process is an Alumina-resin composite part. The solid loading of Alumina powders is 65wt%. Based on the thermal analysis (TG-DSC) of the composite materials, the de-binding and sintering procedures for Alumina are designed as follows.

5.1 De-binding and sintering schedules

In the de-binding step, the organic composition in the green part is fully burned out. To avoid delamination and pores, the green sample is put in a vacuum muffle furnace and debinded under a temperature of 600°C for 3 hours. After the polymers in the green part have been burned out, a high-temperature sintering process is carried out to improve its density. The sintering of the debinded sample is conducted in a regular muffle furnace at 1650°C for 1 hour. The heating schedules for both de-binding and sintering of the Alumina gear part are shown in Figure 11.

Figure 11: Post processing of Alumina green parts. a) De-binding schedule; (b) sintering schedule.

5.2 Testing Results of Sintered Samples

The Alumina green part and the related sintered part are shown in Figure 12a and 12b, respectively. The diameter of the green part is 15mm. After the de-binding and sintering procedures, the diameter of the gear part is ~11.6mm. The shrinkage of the presented ceramics fabrication process for the gear model is ~22.7%. Such shrinkage can be compensated by enlarging the original CAD model by an accordingly estimated ratio.

Figure 13 shows the Scanning Electron Microscope (SEM) images of green and sintered parts. Samples in the shape of a simple block are fabricated using the same materials and process settings as the ones used in the fabrication of the gear model. The cross-sections of the block samples before and after the post processing are prepared and put under a SEM. Figure 13a shows that the polymer and Alumina particles are mixed uniformly through the entire volume, although some agglomerates in the green part may still exist. The average size of the Alumina particles in the green part is less than $1\mu\text{m}$ due to the ball milling process. Figure 13b shows large Alumina grains with obvious boundaries are generated after the de-binding and sintering processes. Some improvements in the post-processing to remove pores in the final part include adding isostatic pressure during the sintering process. A density of 93.2% of true Alumina density ($3.95\sim 3.98\text{g/cm}^3$) is obtained in the sintered block samples.

Figure 12: A test case of a gear model. (a) The green part of an Alumina gear model; (b) the fabricated Alumina gear after the de-binding and sintering procedures.

Figure 13: The SEM images of different samples. (a) Alumina green part; (b) sintered Alumina part.

6 Conclusions and Future Work

In the paper a tape-casting-integrated MIP-SL process has been presented for fabricating viscous ceramic suspension. Uniform ultrathin layers can be recoated by integrating the bottom-up projection approach and the ceramic tape casting process. A doctor blade first spreads viscous slurry into thick layers. A two-channel design and related platform motions are then used to achieve a desired layer thickness that can be much smaller than the blade-recoated layer thickness. The design can also facilitate the layer separation after each layer has been fabricated. Benefits of using the bottom-up projection and tape-casting methods have been analyzed for the ceramic suspension based SL process.

The preparation of ceramic suspension and its curing characteristics have been presented. An experimental prototype system has been developed to test the capability of the presented ceramic fabrication process. Several test cases have been fabricated using Alumina, Zirconia and PZT powders. The sintering results of an Alumina part example show the developed post-processing procedures can fabricate ceramic components with good density.

Some of our future work include: (1) investigating the post-processing procedures for other types of ceramic materials especially PZT; (2) studying physical properties of sintered ceramic components and exploring the effects of different process parameters on the related properties; and (3) further improving the ceramic fabrication process to achieve an even higher density.

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Figure 1: Different methods of bonding ceramic powders in additive manufacturing

Figure 2: Two recoating processes for the top-down projection method.

Figure 3: MIP-SL process using the bottom-up projection method.

Figure 4: Green part fabrication using tape casting integrated MIP-SL.

Figure 5: Process planning for the tape casting integrated MIP-SL process.

Figure 6: The velocity profile in the blade recoating.

Figure 7: Drag force during the layer detachment

Figure 8: A developed ceramics fabrication testbed. (a) A prototype system using the tape casting integrated MIP-SL process; (b) the graphical user interface of the developed process control software system.

Figure 9: Flow chart of the tape-casting-integrated MIP-SL process.

(a)

Figur10: Green parts fabricated by the tape-casting-integrated MIP-SL process.

Figure 11: Post processing of Alumina green parts. a) De-binding schedule; (b) sintering schedule.

Figure 12: A test case of a gear model. (a) The green part of an Alumina gear model; (b) the fabricated Alumina gear after the de-binding and sintering procedures.

Figure 13: The SEM images of different samples. (a) Alumina green part; (b) sintered Alumina part.

	SLA (Griffith, 1996; Dufaud, 2002)	MIP-SL (Chabok, 2012)	Our method
Energy source	Laser	Mask Image	Mask Image
Light direction	Top-down	Bottom-up	Bottom-up
Required amount of Material	Full tank	Height < 10mm	Height < 2mm
Layer thickness	50-100 μ m	<10 μ m	<10 μ m
Recoating shear rate	Low	Low	High
Diluent Solution	Yes	Yes	No or little

Table 1. A comparison between different ceramic-suspension-based SL processes

Type	Cure depth (μ m)	d50 (μ m)	n_p @ 632.8nm	Density (g/cm ³)	Resin	Cure time (s)
PZT	23.6	5	2.397	7.7	SI500	10
Zirconia	82.0	0.09	2.208	6.05	SI500	10
Alumina	250.6	1.1	1.766	3.95	SI500	10
Pure resin	750.0	NA	1.382-1.441 [†]	1.10	SI500	10

Table 2. Physical properties and cure depths of ceramic powders with 65wt%. Note: [†]refer to (Griffith, 1996).

	Curing time (s)	Layer thickness (μ m)	Blade gap δ_{blade} (μ m)	Recoating speed V_r (m/s)	Sliding speed V_s (m/s)
Alumina	15/10	50	250	0.05	0.05
Zirconia	25/20	30	150		
PZT	60/30	10	100		

Table 3. Main process parameters used in the fabrication process