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Micro-scale feature fabrication using immersed surface accumulation☆

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ABSTRACT

Most additive manufacturing (AM) processes such as stereolithography (SLA) and selective laser sintering (SLS) use a layer-by-layer fabrication approach. They cannot be used to fabricate geometric features on the surfaces of a pre-existing three-dimensional (3D) object. In addition, existing AM processes are mainly based on a single size scale, e.g. macro-scale or micro-scale, and cannot be used to build a macro-scale object with micro-scale features on its surfaces. In this paper, we present a novel immersed surface accumulation process that can fabricate micro-scale features on macro-scale surfaces. In the process, a surface-based light guide tool is immersed inside liquid resin to fabricate high-resolution features on the surfaces of a pre-existing object. The system design and process settings to fabricate 3D features are presented. The relation between process control and related fabrication property is discussed. Two test cases are presented to demonstrate the effectiveness of the newly developed immersed surface accumulation process.

1. Introduction

Additive manufacturing (AM) technology can fabricate freeform surfaces and complex inner structures [1]. Some AM processes such as stereolithography (SLA), selective laser sintering (SLS), and fused deposition modeling (FDM) have been widely used in various industries. Based on a layer-based fabrication approach, a computer-aided design (CAD) model is first sliced into a set of two-dimensional (2D) layers. Accordingly, materials are deposited to form object layer by layer. Most AM processes can only fabricate a CAD model from scratch; they cannot build 3D features on a pre-existing object. However, for physical and biological studies, the surface modification using micro-scale features is desired and sometimes critical in order to achieve certain functionality. Fig. 1 shows some examples of micro-scale features in nature that serve critical functions for animals and plants, including optical filtering [2,3], self-cleaning [4], force reducing [5], and waterproofing [6]. The capability of fabricating micro-scale features on the surface of an object to mimic nature's designs is critical and could have immense applications [7]. This paper presents a new AM process trying to address such a critical need.

In our previous work, the point-based and line-based computer numerical controlled (CNC) accumulation methods have been developed for building features on the surface of a pre-existing object [8–11]. However, due to the size of the used light beam tool and its limited control on resolution, both the point-based and line-based CNC accumulation methods cannot fabricate micro-scale features. In comparison, the existing AM processes that can fabricate high-resolution micro-scale features usually lack the flexibility of building around inserts [12]. The two-photon polymerization (TPP) process is a unique process that can fabricate complex 3D microstructures with no topological constrains. The reported resolution can be smaller than 100 nm [13]. However, only transparent resin and limited depth can be applied in the TPP process. It is also time-consuming to fabricate patterned micro-features in a large area. To fabricate biomimetically inspired surface for hydrophilic and hydrophobic study, the molding process was also used [7]. However, only simple shape can be fabricated by the molding process, and the structures with over-hang features cannot be fabricated. The electrospinning method has also been used to fabricate micro-scale biomimetic structures. However, the process is time consuming and the fabricated geometric shapes have limited complexity [6]. In addition, the laser-based 3D micro-scale printing technology has previously been used to fabricate the shark

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Nomenclature

$G(i, j)$	Gray scale of the pixel in i^{th} row and j^{th} column of a 2D projection image
$L(i, j)$	Light intensity of the pixel in i^{th} row and j^{th} column of a 2D light beam in the light guide tool
$H(i, j)$	Adjusted gray scale of the pixel in i^{th} row and j^{th} column of a 2D projection image
C_d	The cure depth of material
L	The distance between the light guide tool and the pre-existing object
r,g,b	The initial distance between the light guide tool and the pre-existing object
R	The color level of an image captured by a CMOS camera
F_M	The attaching force between cured resin and the basis or the previously cured layers
F_T	The attaching force between cured resin and the tip surface of the light guide tool

skin features as shown in Fig. 1(e) on a flat plate [5]. Comparing with these micro-scale fabrication processes, the mask-image-projection based SLA (MIP-SL) can deposit a layer with a single light exposure; in addition, a projection image controlled by a digital micromirror device (DMD) can have a dimension ranging from a few millimeters to over 250 mm [14–19]. Hence the fabrication process based on the MIP-SL process can have fast fabrication speed and achieve high resolution if a small projection area is used.

In this paper we extend the point-based and line-based CNC accumulation processes to the surface-based accumulation process and name it the immersed surface accumulation (ISA) process. The main idea is to use high-resolution 2D mask images instead of a single point spot or a line beam to accumulate materials on an inserted object in liquid resin. Hence the surfaced-based CNC accumulation process can be used to fabricate micro-scale 3D features on an inserted object. Combining both dynamically controlled light beam with the movement of light guide tool, the process can accumulate high resolution features on the surface of a macro-scale object. To achieve the desired fabrication capability, a set of light guide tools are designed by combining objective lens with optical fiber or acrylic rod so that the light beam can reach 2.5μm per pixel. In addition, the light guide tool is immersed inside the resin tank; consequently, different 2D patterned light beams can be dynamically projected during the movement of the light guide tool to accumulate material into desired 3D shapes. In the paper, the photocuring properties of liquid resin are studied; based on them, complex 3D features can be built using a set of 2D patterned light beams with continuous light exposure. The fabricated 3D features can have smooth surface quality and achieve a resolution as high as 5μm. The fabrication speed based on the process is also fast due to the continuous light exposure.

Similar to the widely used CNC machining process, the light guide tools in the immersed surface accumulation process can have various shapes and sizes. For a given CAD model, an appropriate tool can be selected based on the 3D features and the object surface to be fabricated on. Experiments on several designed test cases have been performed to illustrate the capability of the developed ISA process. The immersed surface accumulation process shows significant strengths on fabricating micro-scale features on macro-scale object surfaces. The new AM process, with the capability of building around inserts and fabricating multi-scale geometric features using multiple types of materials, could enable various physical and biological applications.

2. Immersed surface accumulation system design

The immersed surface accumulation is a non-layer-based additive manufacturing process and is complimentary to the multi-axis CNC machining process [8]. As a 3D micro-scale feature fabrication technology, the ISA process has an optical system, a mechanical system, and a light guide tool changing system. Similar to the point-based CNC accumulation process [8], the ISA process uses a light guide tool to cure features in liquid resin. Since material is accumulated along the moving direction of the light guide tool, there is no obvious stair-stepping effect on the built features [10]. In comparison, the point-based CNC accumulation cannot fabricate micro-scale features since it uses accumulation tools whose sizes are over 0.3 mm; in the ISA process, a DMD-based light guide tool is used as the accumulation tool, which is immersed in liquid resin to build micro-scale features on a given object. In addition, a tool changing system is developed to change the accumulation tools that are used to build 3D features on the top or side surfaces of an inserted object. Either the light guide tool or the pre-existing object can be moved in the fabrication process. In our system setup a bottom-up frame is used so that less resin can be used in the fabrication of micro-scale features.

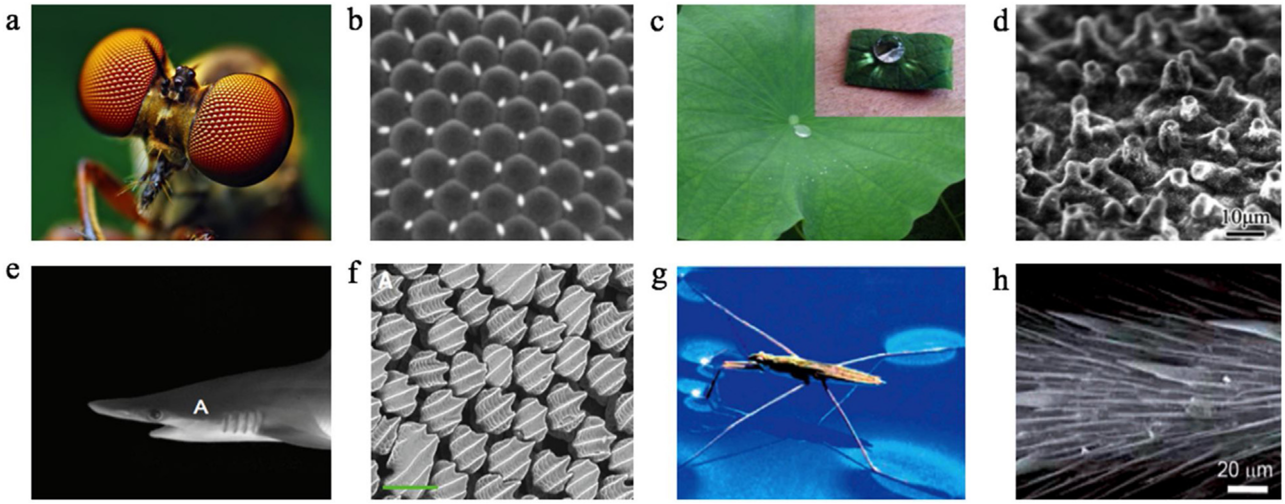

Fig. 1. Functional micro-scale surface features in nature. (a, b) Fly eyes [2] and the micro-feature on them [3]; (c, d) a lotus leaf and the micro-features on its surface [4]; (e, f) a shark and the micro-features on the shark skin [5]; (g, h) a water strider and the micro-features on its feet [6].

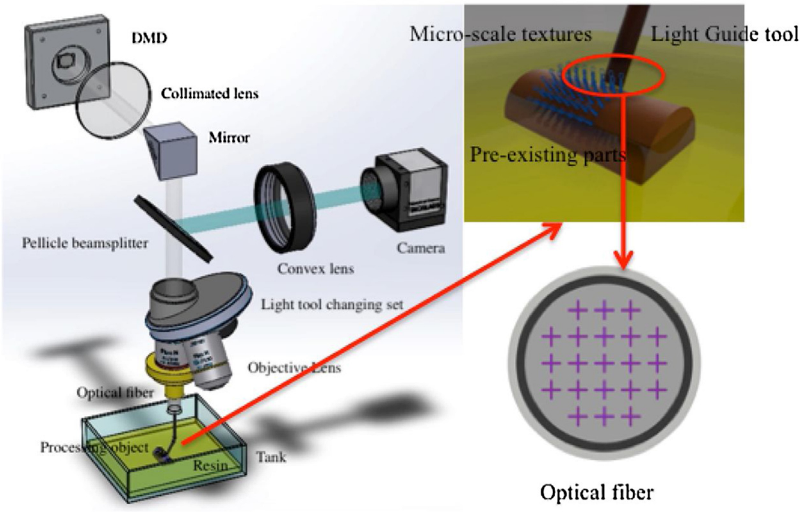

Fig. 2. The layout of the immersed surface accumulation imaging system.

2.1. Optical system

The optical system of the ISA process contains a bulb, a DMD chip, and a set of lenses. The power of the light bulb used in our experimental system is 2500 lm. Its illumination beam is first collimated by a series of lenses. The light source is considered as a point source and the light from the bulb is collimated before reaching the DMD chip. An illustrate diagram of the accumulation tool with the DMD-based optical system is shown in Fig. 2. The DMD chip can be controlled to individually rotate each of its micromirrors ±10–12° to set its state on or off. In the ***on*** state, the light from the bulb is reflected onto the lens, making the pixel appear bright on the top surface of the light guide tool. In the ***off*** state, the light is directed elsewhere, making the pixel in the light beam turn to be dark. By controlling the angle of the micromirrors, each pixel in the light beam can have different brightness. An achromatic doublets lens with focus $f_{ad} = 150$ mm is used to converge the light beam and to reduce the light distortion. A filter lens is used to block the light with wavelength other than 405 nm. The collimated light beam then goes through a 4× objective lens with the focus distance $f = 15\,mm$. The objective lens determines the desired dimension of the light beam. The distance between the objective lens and the collimated lens can be changed based on the optical design (see Fig. 2). The dimension of the accumulation light beam used in our system is 3.67 × 2.75 mm. Since the resolution of the DMD chip is 1920 × 1080, the resolution of the light beam in our system setup is 2.5 μm per pixel.

To use the dynamically controlled light beam to fabricate micro-scale features, the light beam on the tip of the accumulation tool needs to be correctly focused. However, since the accumulation image is rather small, the focusing detail cannot be directly observed. Consequently, a vision system is integrated in the optical design in order to observe the controlled light beam. This vision system contains a beam splitter, a convex lens, and a complementary metal-oxide semicondustor (CMOS) camera. The light beam with a 2D micro-scale pattern goes back to the objective lens, which is then reflected by the beam-splitter. A CMOS camera is mounted behind the convex lens so that the light beam reflected by the beam-splitter can go into the convex lens and is finally captured by the CMOS camera. The captured image is displayed on a computer monitor with 50× magnifications. Based on it, the accumulation image can be observed to accurately adjust its focus. In addition, as discussed in Section 4.1, the vision system can also be used to determine the relative position of the light guide tool and the surface of an inserted object.

2.2. Accumulation tool and hardware design

In the point-based CNC accumulation process, the accumulation tool is made up of a small optical fiber that can transmit light from a light-emitting diode (LED). Hence liquid resin can be solidified and accumulated by moving the light guide tool on an object surface. In the ISA process, a light guide tool is also needed to transmit patterned light beam. We construct the light guide tool using two types of material, a flexible optical fiber and a rigid acrylic rod. (1) Because an optical fiber is flexible, we can easily mount it to a motion system to position the 2D patterned light beam in different directions and locations. Furthermore, an optical fiber can transmit the input light without the length constrain. Hence, the optical fiber can be long enough to enable the DMD-based optical system to be located anywhere away from the inserted object. We mount one side of the optical fiber on the bottom of the objective lens with a designed distance; the other side of the fiber is coated with a thin layer of Polydimethylsiloxane (PDMS), which can help the separation of cured resin from the optical fiber [14]. Thus, after being reflected by the DMD chip and going through the objective lens and the light guide tool, the focused light beam can be generated on the tip surface of the light guide tool (refer to Fig. 3d). A disadvantage of the optical fiber is it needs to use multi-core due to the light transmission effect as shown in Fig. 3b. The smallest core size limits the highest resolution that the ISA process can achieve. (2) Another material used in the light guide tool is an optical acrylic rod as shown in Fig. 3a. After the light goes through the objective lens and the acrylic rod, the light beam with 2D micro-scale pattern can be focused on the top surface of the acrylic rod (refer to Fig. 3c). To generate focused light beam, the height of the acrylic rod needs to be equal to the focal distance of the objective lens. Taking advantage of the virtual detection system, we can adjust the distance between the light guide tool and the objective lens by a precise linear stage so that focused light beam can be generated on the tip surface of the light guide tool. The layout of the light guide tool based on the acrylic rod and the optical fiber are shown in Fig. 3a and b, respectively. Different from the optical fiber, the highest resolution of the light guide tool using the acrylic rod is only determined by the DMD-based optical system. A drawback of the acrylic rod is that it is rigid with fixed length. Hence, for the light

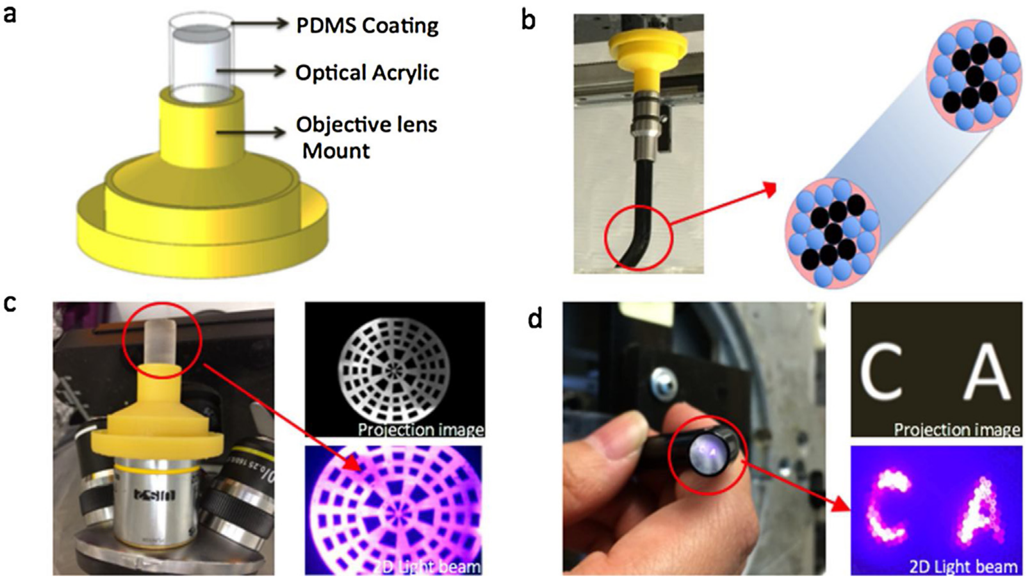

Fig. 3. The design of light guide tools. (a) A light guide tool design using an optical acrylic rod; (b) a light guide tool using an optical fiber with multi-cores; (c) 2D patterned light beam generated by the light guide tool using an optical acrylic rod; and (d) 2D patterned light beam generated by the light guide tool using an angled optical fiber with multi-cores – the dimension of each core inside the used fiber is 80 μm.

guide tool based on the acrylic rob, a multi-axis motion system is used to move the inserted object instead of the light guide tool.

In the ISA process different light guide tools may be used depending on the features to be built and the geometric shape of the inserted object. For example, a light guide tool with straight head or with a 90° tip angle can be used in fabricating micro-scale features on surfaces with different surface orientations (refer to Fig. 4). As shown in the CNC machining system, an automatic tool changing system can be used to change the machine tools based on the fabrication requirements. Similarly, a light guide tool changing system can also be developed for the ISA process to address the needs of building features on different object surfaces. We believe the light guide tools with even more head angles and different tip shapes can be developed. Accordingly, a suitable light guide tool can be used in the fabrication process.

Similar to the multi-axis CNC machining process, multi-axis movements can be used in the immersed surface accumulation process. In addition to precise linear stages to drive the inserted object in the *X*, *Y*, and *Z* axes, rotation stages can be combined to change the angle of the pre-existing object so that features can be deposited from different surface orientations. In our system, a high performance 6-axis motion control board with 28 bidirectional I/O pins from Dynomotion Inc. (Calabasas, CA) is used to drive the linear and rotation stages. Fig. 5a shows the ISA setup, which has the aforementioned imaging system, the visual detection system, the light guide tool changing system, and the motion control system.

2.3. Software design

A software testbed for the surface-based CNC accumulation process has been developed using C++ language with Microsoft Visual Studio C++ complier. The testbed integrates the modules of mask image planning, light beam generation, and the motion control. It also synchronizes the light beam generation with the controlled movement of the inserted object. The graphical user interface of the developed software system for the ISA system is shown in Fig. 5b.

3. Photocuring performance of the immersed surface accumulation

The light intensity of the 2D patterned light beam transmitted by the light guide tool needs to be controlled in order to achieve high-resolution micro-scale fabrication. Experiments are conducted to analyze the relation between the gray scale level of the mask image and the photocuring result of liquid resin. Based on them, the gray scale level of each pixel is adjusted to generate the desired light beam patterns that can be used to fabricate the given micro-scale features. Since the light guide tool is immersed in liquid resin, the gap between its tip surface and the object surface is filled with liquid resin all the time. One important consideration is how to control the movement of the light guide tool so that the newly cured resin can be attached to the previously built layers instead of the accumulation tool [8]. Another important consideration is to address the pixels' overlapping effect in the light beam for the micro-scale fabrication [20]. We discuss the relation between the energy input of a light beam and the related fabrication quality in this section. We will discuss the attaching forces in the immersed surface accumulation process in Section 4.

3.1. Micro-scale 2D patterned light beam generation

The light intensity of a 2D patterned light beam transmitted by the light guide tool is not uniform. A test pattern based on an acrylic rod is shown in Fig. 6a and is used to build micro pillars to test the non-uniformed light distribution. Due to the non-uniformed light intensity distribution, some portions of the micro-pillars are over-cured while some other portions cannot be sufficiently cured using the same exposure time. Such non-uniformed light intensity from the light guide tool significantly impact the accuracy and resolution of the ISA process. To address the problem, an approach to adjust light intensity has been developed, in which the light intensity distribution of 2D patterned light beam is calibrated, and accordingly gray scale pixel values are used during the mask image planning. Because the light intensity of neighbouring pixels has similar light intensity, we divide the 2D patterned light beam into a set of blocks. Each block is a square area with 25 × 25 pixels. We set the same

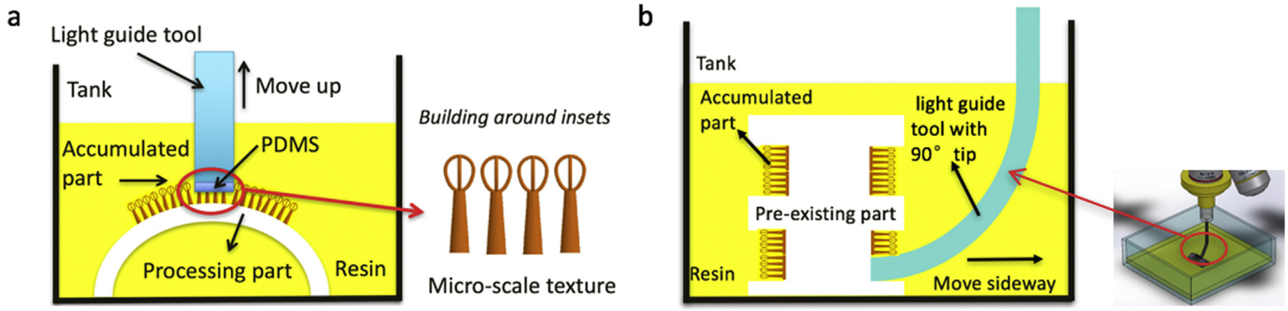

Fig. 4. An illustration of the fabrication process using light guide tools in the immersed surface accumulation process. (a) Building around inserts using a light guide tool with a straight head tip; and (b) adding micro-scale features on a side surface using a light guide tool with 90° tip.

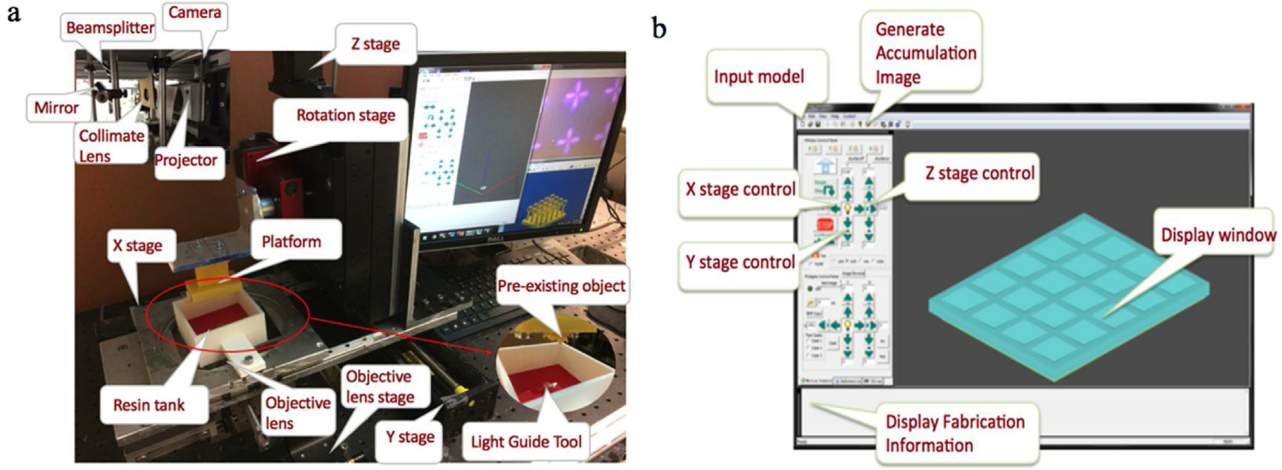

Fig. 5. The hardware and software systems in the immersed surface accumulation system. (a) The physical setup of the immersed surface accumulation system; and (b) the graphical user interface of the developed software system.

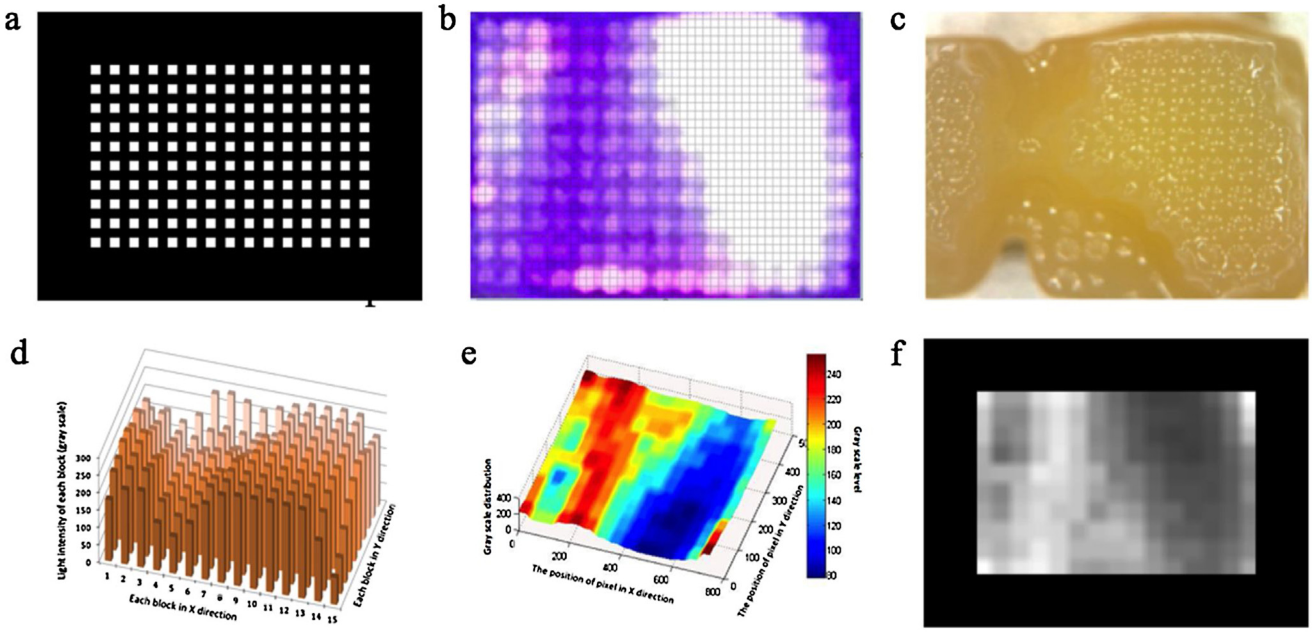

Fig. 6. The light intensity distribution of 2D patterned light beam. (a) Test pattern sent to DMD with gray scale level of 255; (b) the focusing image captured by a CMOS camera; (c) the fabricates result by the tested light beam with an exposure time of 0.8s; (d) the light intensity distribution model of the 2D patterned light beam; (e) the gray scale database of 2D pattern; and (f) the gray scale level distribution of 2D pattern. (For interpretation of the references to color in text, the reader is referred to the web version of this article.)

gray scale value for all the pixels in each block, and their gray scale values are initially set at 255. A CMOS camera is used to capture the focusing image of such a patterned light beam (refer to Fig. 6b), which contains three information components – red, green, and blue values. To calculate the light intensity from these three colors, we converted the color image into a gray scale *G (i,j)* by using the weighted average method (see Eq. (1)). The calculated gray scale levels of the image represent the light intensity of pixels in the 2D patterned light beam [20,21]. After identifying the effective exposure area, the light intensity *L(i,j)* of each effective block can be calculated (refer to Eq. 2). The original light intensity distribution of the 2D patterned light beam is shown in Fig. 6d.

$$G(i,j) = 0.30r(i,j) + 0.59g(i,j) + 0.11b(i,j) \tag{1}$$

$$L(i,j) = \frac{\sum_{m=50i;n=50j}^{m=25\times(2i+1)n=25\times(2j+1)} G(m,n)}{25 \times 25} \tag{2}$$

Based on the light intensity distribution of the 2D patterned light beam, the gray scale values of an input 2D pattern can be modified; at the same time, the visual detection system can be used to dynamically capture the focusing images of these 2D light patterns. For each patterned light beam, the light intensity of each pixel is calculated based on the gray scale levels of the captured image. Furthermore, we use different gray scale levels in the 2D patterned light beam to build micro-pillars. The mathematical model is established to fit the relation between the light intensity variations and the gray scale levels of the pixels in the 2D patterned light beam. Based on the light intensity models of each block, the gray scale level *H(i,j)* of each block can be adjusted to reach the same light intensity value *Lmin*. Finally, the light intensity distribution of the whole 2D patterned light beam can reach the same level after several iterations. Using the adjusted gray scale level *H(i,j)* derived from the light intensity model for each pixel, the gray scale distribution database for the whole 2D patterned light beam can be established based on the bilinear interpolation (refer to Fig. 6e–f). We successfully fabricated uniform pillars at the size of 100*100 μm based on the 2D patterned light beam with adjusted light intensity. The microscope image of the fabricated micro-pillars is shown in Fig. 7. The same mask image planning method is used for building micro-scale features as discussed in Section 5.

3.2. Cure depth control of liquid resin

The moving speed of the light guide tool is determined by the cure depth of the photocurable resin used in the fabrication process. That is, the light guide tool needs to maintain an appropriate gap with the surface of a pre-existing object so that the newly cured resin can attach to the existing object. A series of experiments have been performed to study the relation between the cure depth and the energy power of an input 2D patterned light beam. Based on the polymerization principle [22], the classical Beer Lambert's law of the light propagation shows that the cure depth follows Eq. (3).

$$C_d = D_p ln(\frac{E_{max}}{E_C}) \tag{3}$$

When using the ISA process to fabricate micro-scale features, we move up the light guild tool continuously with a controlled speed. The distance between the light guide tool and the surface of the pre-existing object should be less than the cure depth of the resin all the time. For the projection surface area of 3.67mm × 2.75 mm that are set in our accumulation system, the light intensity of the light beam after the aforementioned gray scale adjustment is 30 mw/cm^2. We applied the design of experiments (DOE) to study the cure depth of the photocurable resin by building overhang features as shown in Fig. 8a. The liquid resin used in our experiments is Eglass 3sp from Envisiontec Inc. (Dearborn, MI). Different percentages of multi-wall carbon nanotube (CNT) were added that serves as the light absorber. The fabrication results are shown in Fig. 8b. With different gray scale values used in the input light beam, the cure depth of liquid resin is ranged from 35 μm to 350 μm (refer to Fig. 8d). An illustration of the relationship between the input light energy and the related cure depth is shown in Fig. 8c. After analyzing the experimental data, Fig. 8d shows the relation between cure depth, light intensity, and different percentages of light absorber.

The material is accumulated during the movement of the light guide tool. If the moving speed between the light tool and the pre-existing object is too fast, the newly cured resin portion may not be able to attach to the previously cured resin. Hence the continuously moving speed of the light guide tool needs to be set based on the tested cure depth. The fabricated micro-scale cones by the layer-based SLA process and the ISA process that uses continuous tool movements are shown in Fig. 8e and f, respectively. The surface of the fabricated cones using the immersed surface accumulation process is much smoother than the layer-based SLA process. No stair-stepping effect is observed on the side surfaces.

3.3. Non-linear exposure time setting

The light distribution of each pixel in the 2D patterned light beam follows Gaussian function [20] (refer to Fig. 9a). The light intensity of neighbouring pixels overlaps and convolutes into accumulated light intensity as shown in Fig. 9b [20,21]. Hence, if the same exposure time is used for all the pixels, the light energy absorbed by the resin in a portion with bigger exposure area will be larger; consequently, the resin in the portion can be overcured compared to the portion with a smaller exposure area if the same exposure time is set for them. A set of experiments have been performed, in which the micro-scale cone arrays with different 2D patterned light beam are fabricated (refer to Fig. 9c). The exposure time increases non-lineally with the decrease of the exposure area in the 2D patterned light beam. The test parameters and the fabrication results are shown in Fig. 9d. With the increase of the exposure area in the 2D patterned light beam, the exposure time required in the accumulation process will be less. Accordingly, the moving speed of the light guide tool can be increased to maintain the same curing result.

4. Process planning of the immersed surface accumulation

Since the light guide tool is immersed inside the liquid resin and the 2D patterned light beam is located on the tool's tip surface in the ISA process, liquid resin is solidified at where the light guide tool touches liquid resin. For an input CAD model of 3D micro-scale features, the 2D patterned mask images are first generated by slicing the CAD model. After the inserted object is mounted on the motion stage, an initial position of the light guild tool is identified based on where the tool's tip surface touches the object surface. After fixing the light guide tool, the moving speed of the pre-existing object depends on the curing characteristic of liquid resin as discussed in Section 3. Hence the feature fabrication process relies on the steps including the initial position identification, and the attachment of the newly cured resin compared to its separation from the light guide tool.

4.1. Initial position identification

To build micro-scale features on an object surface, the initial position is critical since the deformation of the PDMS film on the tool tip could be larger than 100 μm under pressure. Such a distance is significant for the micro-scale feature fabrication. If the PDMS film is deformed, there would be no gap between the light guide

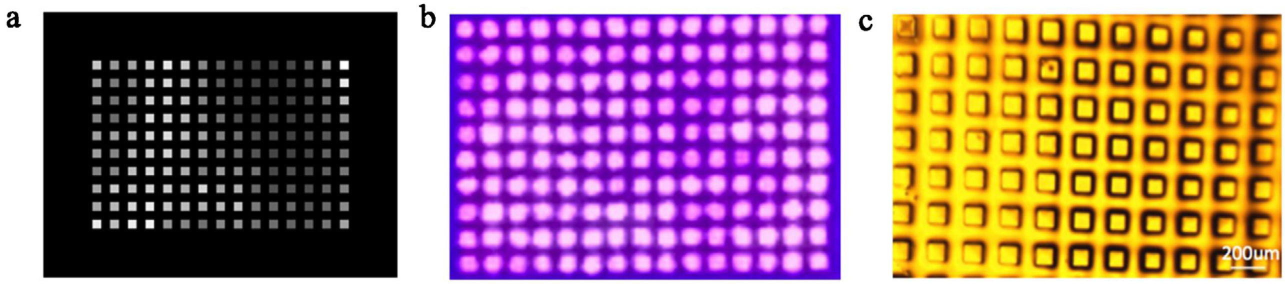

Fig. 7. A study of the uniform light intensity distribution in the 2D patterned light beam. (a) The 2D patterned image generated based on the light intensity database for fabricating a set of micro-pillars; (b) the focusing image of the 2D patterned light beam captured by a CMOS camera; and (c) the micro-pillar array fabricated by the 2D patterned light beam.

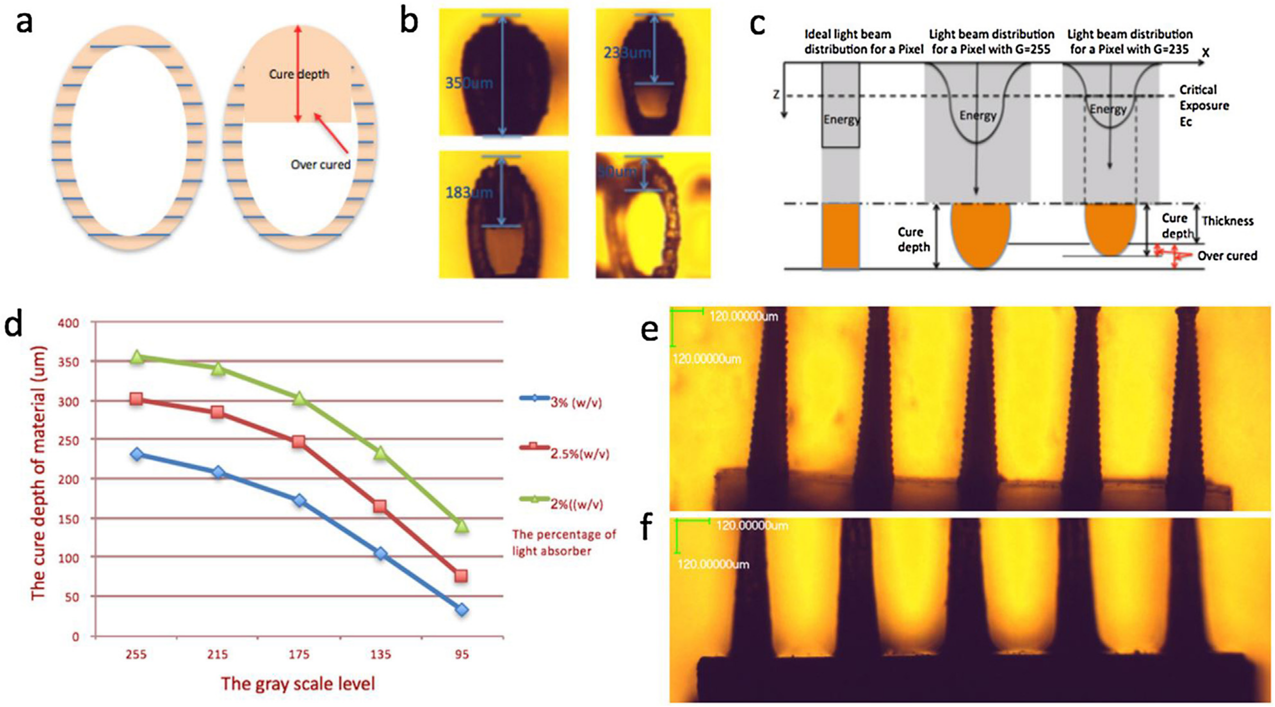

Fig. 8. The curing depth control of liquid resin. (a) The schematic design of elliptical shape ring; (b) the experimental results of the curing depth with different percentages of light absorber; (c) an illustration of the relation between the light energy and curing depth of resin; (d) the experimental results of curing depth, grayscale levels of input light, and different light absorbers; (e) the cone fabricated by the layer-based SLA process; and (f) the cone fabricated by the immersed surface accumulation process (with the moving speed of 50 μm/s).

tool and the object surface when the inserted object is moved away. Hence the initial portion of the fabricated micro-scale features will be missing due to the lack of resin refill in the beginning of the fabrication process. To avoid adding pressure to the PDMS film, it is critical to identify the relative position of the light guide tool and the inserted object in each building direction (refer to Fig. 10a). Taking advantage of the visual detection system, an imaging analysis method is used in the ISA system. As the inserted object is moved closer, the distance L between the accumulation tool and the object surface decreases; hence the volume of the liquid resin between the two surfaces are reducing. In the visual detection system of the ISA system, the color of the liquid resin in the captured image becomes lighter with the decrease of distance L. When the outer surface of the object touches the top surface of the PDMS film, the pre-existing object pushes all the resin out and will appear in the captured image. By analyzing the dynamically captured images, the relationship between the initial distance l and the color level R in the captured images can be fitted. Based on the above image analysis process, the distance l can be dynamically estimated during the platform movement. Finally, the platform can be moved to an initial position with the distance l value close to zero.

4.2. Attachment of cured resin

Liquid resin is photocured during the immersed surface accumulation process, and the newly cured resin needs to be deposited on the previously cured resin portion instead of on the light guide tool. In our previous study [8–10], the relation between the attaching force and the separation force of the cured resin has been established. In addition, the fabricated features need to overcome the drag force F_d that relates to the viscosity of liquid resin during the movement of the inserted object. For a slow moving speed, the drag force could be omitted. Hence the main consideration is the surface property of the materials that immediately contact the cured resin. Suppose the attaching force between the cured resin and the pre-existing object or the previously cured resin is F_M, and the attaching force between the cured resin and the PDMS film is F_T. If $F_M > F_T$ during the whole building process, the newly cured resin will always attach to the inserted object; hence the building

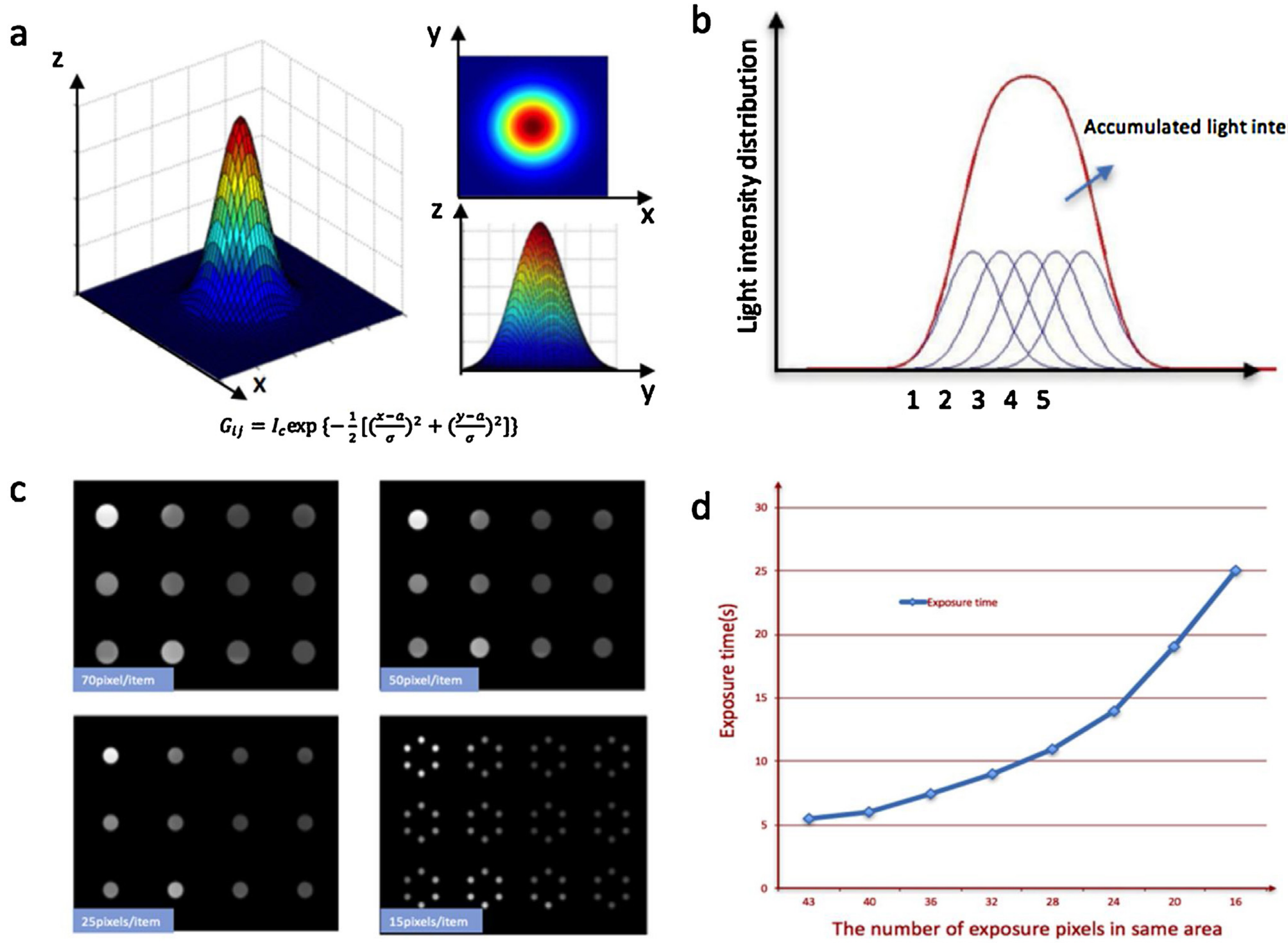

Fig. 9. The exposure study of liquid resin. (a) An illustration of Gaussian function for the light energy distribution of a pixel in the projection image; (b) the overlapping effect of light energy in neighbouring pixels; (c) the 2D patterned images used to fabricate the micro features with different exposure areas; and (d) the experimental results of exposure time versus exposure area in 2D patterned light beam.

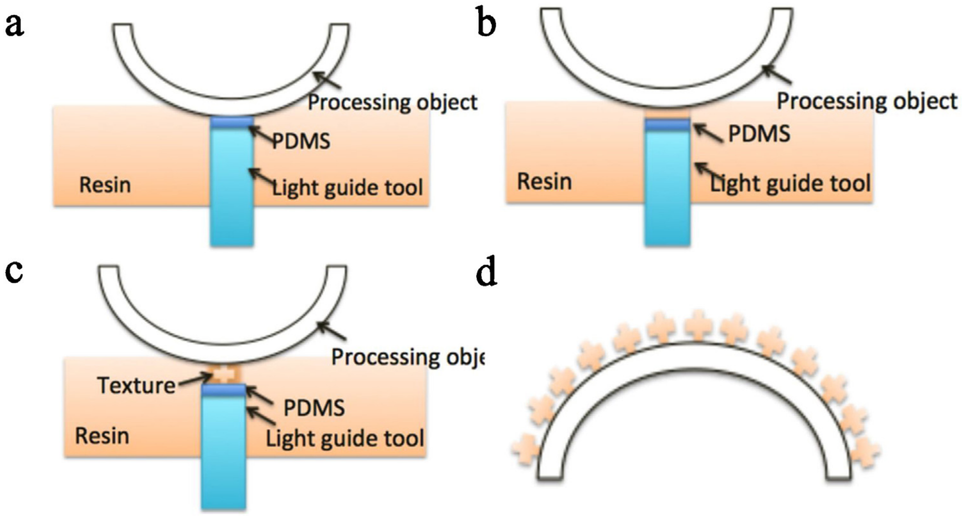

Fig. 10. An illustration of positioning the light guide tool. (a) Initial distance $Li = 0$; (b) liquid resin fills in when the inserted object moves up; (c) One feature is fabricated on the object surface; and (d) multiple features can be built on the surface of the pre-existing object.

process will be successful. Otherwise, if $F_T > F_M$, the cured resin portion will attach to the light guide tool during the tool movement; thus the building process will fail. Based on our previous study [8], we can successfully add high-resolution features on the inserted objects made of plastics and glass. Furthermore, the shape of the light guide tool will affect the micro-scale features that can be fabricated. Similar to the CNC machining process, the movement of the light guide tool should also avoid the collision between the tool

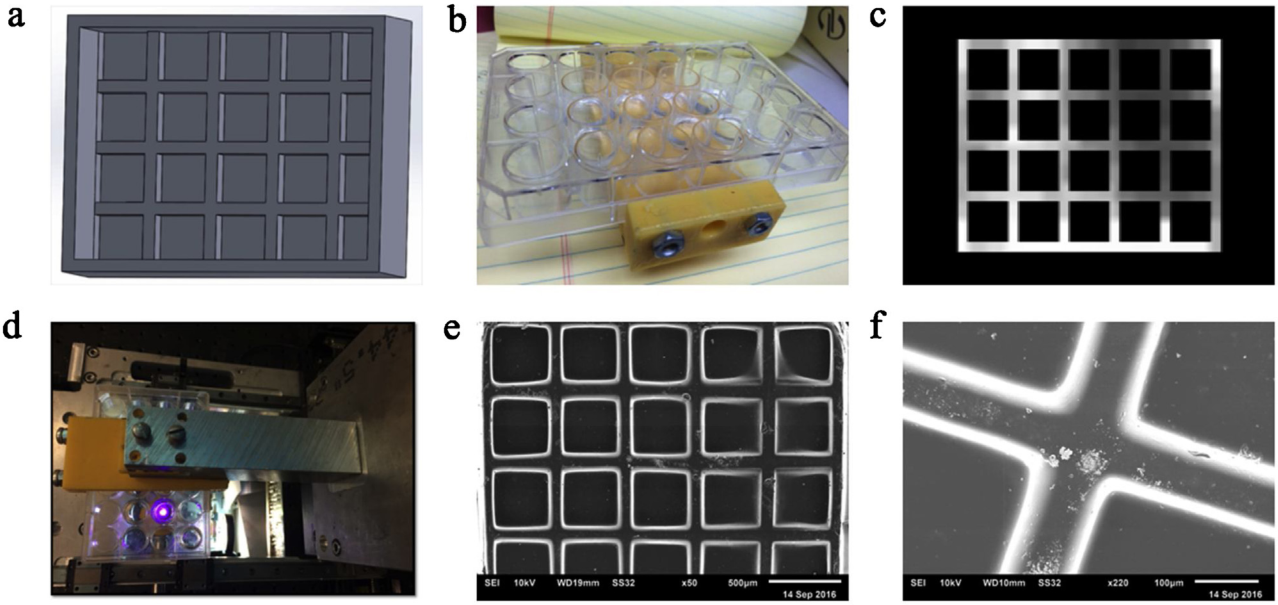

Fig. 11. The test case of scaffold walls fabricated by the immersed surface accumulation process. (a) CAD model of scaffold wall with 150 μm height; (b) the physical model of 24-well cell culture plate that is injection-molded; (c) 2D patterned projection image; (d) the building setup captured during the fabrication process; (e) the SEM image of the fabricated scaffold wall – top view; and (f) the SEM image with a closer view on the scaffold wall that is fabricated inside the 24-well cell culture plate.

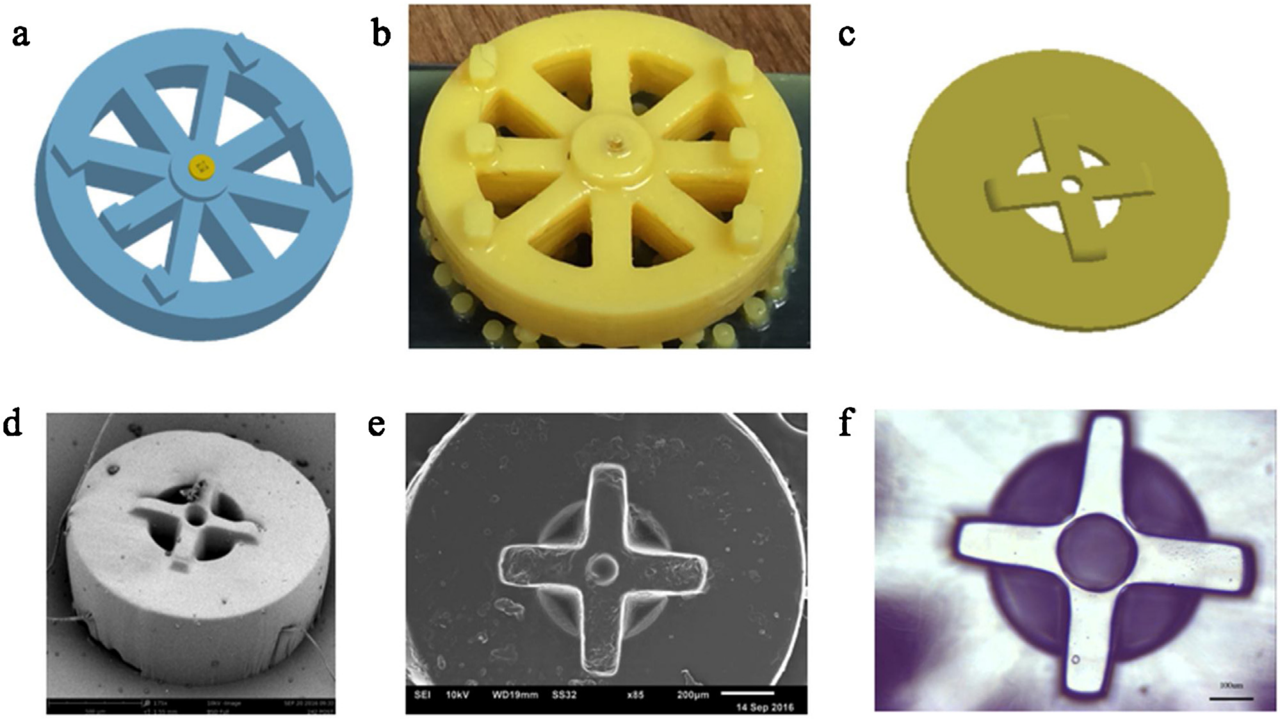

Fig. 12. A test case of an optical filter fabricated by the immersed surface accumulation process. (a) The CAD model of an optical filter with an optical holder; (b) physical model of the optical holder fabricated by the MIP-SL process with micro-scale optical filter added; (c) the design of the micro-scale optical filter to be added on the optical holder; (d) the SEM image of the side view of the micro-scale optical filter added by the immersed surface accumulation process; (e) the SEM image of the micro-scale optical filter (top view); and (f) the microscope image of the top surface of the fabricated micro-scale optical filter. US version: (For interpretation of the references to color in text, the reader is referred to the web version of this article.)

and the pre-existing object and the inserted object as well as the previously cured portions [9].

5. Experimental results and discussions

We have used the immersed surface accumulation process to successfully fabricate several test cases. Two of them are shown in this section including a scaffold wall on a cell culture plate, and an optical filter on an optical holder. The experimental results demonstrate that various micro-scale features with different geometrical shapes and accumulation materials can be fabricated by the developed ISA process.

A scaffold wall was built to verify the capability of the ISA process in building 3D micro-scale features inside a standard 24-well cell culture plate that is fabricated by the injection molding process. The CAD model of the scaffold wall is shown in Fig. 11a. The total height of the scaffold wall is 150 μm and the total *XY* size of the scaffold is 2.5 mm × 2 mm. The width of the block wall is 100 μm. The original cell culture well has a diameter of 15.6mm, which consumes a significant amount of cells as well as chemical solution. In the test, the light guide tool based on the acrylic rod is used to build the new scaffold wall inside the mounted 24-well cell culture plate (refer to Fig. 11b). In order to achieve better surface quality, the slicing thickness of the scaffold wall is set at 3 μm per layer and the gray scale level of the 2D patterned light beam is modified based on the aforementioned curing performance database (refer to Fig. 11c). The setup during the fabrication process is shown in Fig. 11d. The scanning electron microscope (SEM) of the fabricated scaffold wall is shown in Fig. 11e and f. Based on the SEM images, it can be seen the surface quality of the fabricated micro-scale features is satisfactory. In addition, various scaffold walls with different shapes and sizes can be fabricated to enable cell culture study on different wall types.

Another test case that we performed is to build an optical filter on an optical holder as shown in Fig. 12. The CAD model of the optical filter is shown in Fig. 12a. The micro-scale feature that needs to be added is also shown in the figure (in yellow), whose diameter is 1.2 mm (refer to Fig. 12c). Firstly, a macro-scale optical holder was fabricated using the MIP-SL process [14]. Then the optical holder is mounted in our ISA setup as an inserted object. The immersed surface accumulation process is then used to fabricate the micro-scale feature on the top surface of the inserted object (refer to Fig. 12b-the small transparent portion in the center). Since liquid resin is continuously accumulated during the fabrication process, there is no stair-stepping effect on the side surface of the fabricated micro-scale features (refer to the side view of the SEM image in Fig. 12d). Fig. 12e and f shows the magnified views of the fabricated micro-scale feature.

6. Conclusion

A surface-based CNC accumulation process named immersed surface accumulation has been presented including its basic idea, the hardware setup, the software implementation, and the process characteristics. To immerse 2D patterned light beam inside liquid resin, novel light guide tools have been developed using both optical fiber and acrylic rod. Based on the developed light guide tools, a high resolution 3D feature fabrication system has been demonstrated that integrates both mask image projection system and multi-axis motion system. A set of experiments have been performed to identify the curing characteristics of photocurable resin using the developed light guide tools. Based on the experimental results, the process planning of both continuous tool movements and the grayscale values of projection images has been developed for given geometric shapes. Several test cases have been performed. The experimental results show the resolution of the fabricated features is high and the side surface is smooth with no obvious stair-stepping effect.

The immersed surface accumulation process is still in its initial development stage. Some planned future research include investigating applications that are enabled by the newly developed multi-scale AM process, and developing more advanced tool-path planning algorithms for any given geometric shapes.

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