Technical paper

Smooth surface fabrication in mask projection based stereolithography

Yayue Pan, Xuejin Zhao, Chi Zhou, Yong Chen*

Epstein Department of Industrial and Systems Engineering, University of Southern California, Los Angeles, CA, USA

A R T I C L E   I N F O

Article history:
Available online 4 October 2012

Keywords:
Additive manufacturing
Surface finish
Layer stair-stepping
Mask projection stereolithography

A B S T R A C T

The surface finish is critical for applications such as optics, micro-fluid flow and mechanical assembly, in which optical lenses, fluidic channels and rotating components are all required to be smooth. However, the stair-stepping effect is well known in the layer-based additive manufacturing processes, in which a three-dimensional model is approximated by a set of two-dimensional layers. Consequently the fabricated surfaces have poor surface finishes especially those that are close to the horizontal plane. In this paper, a novel approach for achieving improved surface finish is presented for the mask-image-projection-based stereolithography (MIP-SL) process. Theoretical models and parameter characterization are presented for the developed methods. Accordingly, the process planning and calibration approaches for fabricating smooth up-facing surfaces in the MIP-SL process have been developed. Multiple test cases based on various types of curved surfaces have been performed. A comparison of the build results based on the traditional and the newly developed approaches illustrates the effectiveness of our method.

© 2012 The Society of Manufacturing Engineers. Published by Elsevier Ltd. All rights reserved.

1. Introduction

One of the major problems in the layer-based additive manufacturing (AM) processes is the poor surface finish associated with the layer stair-stepping effect. As shown in Fig. 1, a given three-dimensional (3D) model is first sliced into a set of two-dimensional (2D) layers. By stacking these 2D layers together, a physical part can be fabricated in an AM process to approximate the original computer-aided design (CAD) model. Due to the use of 2D layers, the fabricated part surfaces especially the ones whose normals are close to the building direction (Z axis) may have big approximation errors. Such poor surface quality limits the use of AM in applications that require smooth surfaces, e.g. the fabrication of optical lenses, 3D micro-channels in microfluidic systems, and various assembly features in mechanism designs.

Since the approximation error depends on the layer thickness used in the slicing of a 3D model, a dominant approach for addressing the stair-stepping effect in AM is to reduce the layer thickness. For example, the layer thickness typically used in a Stereolithography Apparatus (SLA) system is 0.1 mm while the layer thickness used in the latest developed inkjet-based systems (e.g. the ones from Objet Geometries Ltd.) can be as small as 0.012 mm. While the thinner layers in comparison always have less stair-stepping problems, the use of such ultra-thin layer thickness also significantly slows down the building process. In addition to the great sacrifice in building speed, it is challenging for some AM processes to significantly reduce their layer thicknesses. For example, in the SLA process, the spreading of liquid resin into uniform ultrathin layers is well-known difficult due to liquid viscosity.

In this paper, we present an alternative approach for achieving smooth surfaces in the SLA-related processes. The AM process considered in this paper is the mask-image-projection-based stereolithography (MIP-SL) [1]. The MIP-SL process is quite similar to the SLA process. However, instead of a laser as used in SLA, a Digital Micromirror Device (DMD) is used in the MIP-SL process (refer to Fig. 2a). As a microelectromechanical system (MEMS) device, a DMD enables one to simultaneously control ~1 million small mirrors to turn on or off a pixel at over 5 kHz. Consequently mask images can be dynamically defined and projected on a surface area. By replacing a laser with a DMD, the MIP-SL process is much faster than the SLA process.

All the surfaces in a 3D model can be classified based on the Z axis and its surface normal N into: (1) vertical surfaces (N·Z = 0), (2) down-facing surfaces (N·Z < 0), and (3) up-facing surfaces (N·Z > 0). There is no need to specially consider the vertical surfaces since they generally do not contribute to the stair-stepping effect. Approaches such as controlled curing depth [2,3] have been developed for the fabrication of smooth down-facing surfaces. However, there is no good approach for the fabrication of smooth up-facing surfaces since the cured portions related to such surfaces are under liquid resin during the building process.

In this research, we systematically studied the liquid meniscus related to different process parameters that can be controlled in the MIP-SL process. Based on our findings, we developed a
meniscus equilibrium method for the fabrication of smooth up-facing surfaces (refer to Fig. 2b). The key idea of the approach is to closely match the fluid interfaces at the corners of intersecting planes to the related curved surfaces in the input geometry. Hence, a liquid meniscus will be formed at the corners when the cured layers emerge from the liquid. The shape of the meniscus depends on the contact of horizontal and vertical surfaces, and can be modeled by considering the effects of capillarity, suction by gravity, multilayer adsorption and the boundary conditions [4,5]. Accordingly, a process optimization problem can be formulated in order to match the meniscus to the given curved surfaces. The presented method has a better shape controllability over approaches of dipping and flush-curing the build parts or post-processing such as abrasive flow machining [6].

Compared to the use of ultra-thin layers that significantly elongates the building time, the developed techniques enable a much larger layer thickness to be used while achieving better surface finish requirements. Hence significantly reduced building time is expected in the MIP-AM process.

The remainder of the paper is organized as follows. Section 2 presents the models of formed meniscus in various cases. Accordingly, the process planning for building smooth up-facing surfaces is presented in Section 3. Section 4 presents the calibration and planning of meniscus projection images for a given process plan. The experimental setup for performing physical experiments is discussed in Section 5. The test results for various curved surfaces are presented in Section 6. Finally, conclusions with future work are drawn in Section 7.
2. Meniscus modeling in the MIP-SL process

The formation of the interfacial profile of the equilibrium meniscus that is attached to intersecting surfaces is first discussed. Such understanding and related mathematical models will provide the theoretical basis for the process planning and smoothness control in building the up-facing surfaces. As shown in Fig. 3a, given a pair of walls, suppose the length of the horizontal plane is \(b\), and the height of the vertical plane is \(h\). With a finite horizontal plane, the maximum range of the fluid that can rise up on an infinite vertical plane \(y(x = 0, y_{\text{length}} = b) = h_c\). Similarly, with a finite vertical plane, the maximum range of the fluid that can extend along an infinite horizontal plane \(x(y = 0, x_{\text{length}} = h) = b_0\).

Previous research on determining equilibrium shapes of fluid interfaces has been performed [7–11]. The Young–Laplace (YL) equation is the most widely accepted physical analysis of equilibrium meniscus shape. In the analysis, two types of forces, surface tension and pressure, are taken into account. The surface tension is defined with respect to a specific photopolymer resin. It is a thermodynamic quantity measuring the energy required to expand the area of the gas–liquid interface. As shown in Fig. 3b, the YL equation relates the pressure difference \(\Delta P\) across a fluid interface within a gravitational field to the curvature of the interface and the interfacial tension by:

\[
\Delta P = P_1 - P_2 = -\rho g y = \gamma y_{\text{surf}} \times \left(\frac{1}{R_1} + \frac{1}{R_2}\right)
\]

(1)

where \(P_1\) and \(P_2\) are the pressures on either side of the interface between resin and air, \(g\) is gravity acceleration, \(y\) is the height of the meniscus above the horizontal plane surface, \(\gamma\) is the interfacial tension, and \(R_1\) and \(R_2\) are the radii of curvature of the fluid interface. If \(R_1\) can be considered infinite, the problem is simplified to a 2D case. Thus the following Eq. (2) can be derived from Eq. (1):

\[
\rho g y - \gamma y_{\text{surf}} \times \frac{y}{(1 + y^2)^{3/2}} = 0; \quad \frac{dy}{dx}; \quad \frac{d^2y}{dx^2} = \frac{dy}{dx}
\]

(2)

The interfacial tension \(\gamma\) has a relation with the capillary height \(h_c\) and the contact angle \(\theta\) as shown in Eq. (3).

\[
h_c^2 = \frac{\gamma}{\rho g} (1 - \sin \theta)
\]

(3)

So Eq. (4) can be developed according to Eqs. (2) and (3).

\[
\rho g y - \frac{1}{2} h_c^2 \times \frac{\rho g y}{(1 - \sin \theta)(1 + y^2)^{3/2}} = 0
\]

(4)

2.1. Process parameter calibration

The contact angle \(\theta\) in Eq. (4) is the angle at which the liquid resin interface meets the solidified resin surface. Specific to the given liquid and solid system, the contact angle is determined by the interactions between the liquid resin, solidified resin and air interfaces. Researchers reported that \(\theta\) is observed to be independent of volume and gravity and depends only on the surface tension [12,13]. The capillary height \(h_c\) is the maximum height that the fluid can reach on an infinite vertical wall. \(h_c\) is a characteristic length for the fluid subject to gravity and surface tension.

Both parameters (\(\theta\) and \(h_c\)) can be experimentally measured. Based on different \(b\) and \(h\) values, a set of experiments has been designed. The MIP-SL process was used in building the test parts with intersecting horizontal and vertical surfaces. After the horizontal and vertical surfaces have been built, the part is first merged inside liquid resin; it is then lifted up slowly until the horizontal plane is totally outside the liquid resin. A liquid meniscus in contact with the intersecting surfaces will be formed on the part surfaces. After a long waiting time, the liquid volume will reach equilibrium over the horizontal wettable surface area. A mask image is then projected on the meniscus area to cure the liquid resin. The shape of the formed meniscus can thus be captured in the built part. A set of parts with different sized horizontal and vertical planes has been built. Two of such built parts are shown in Fig. 4. Based on the experiments, the contact angle \(\theta\) and the capillary height \(h_c\) can be measured. For the liquid resin used in our experiments (Perfactory SIS500 from EnvisionTEC, Ferndale, MI), it is estimated that \(\theta = 25^\circ\), and \(h_c = 1.40\) mm.

2.2. Meniscus shape analysis and simulation

In the MIP-SL process, suppose \(h\) denotes the height of the vertical plane, \(b\) denotes the length of the horizontal plane, and \(h_c\) and \(b_0\) denote the maximum values that the liquid can reach on the vertical and horizontal planes, respectively. The formed meniscus shapes for different \(b\) and \(h\) values can thus be analyzed based on the following four scenarios: (1) Case 1: \(h > h_c\); \(b > b_0\); (2) Case 2: \(h < h_c\); \(b > b_0\); (3) Case 3: \(h > h_c\); \(b < b_0\); and (4) Case 4: \(h < h_c\); \(b < b_0\).

For each scenario, different boundary conditions can be derived. Hence the formed meniscus shapes are different, and are discussed as follows:

(1) Case 1: both \(h\) and \(b\) can be considered infinite. The related boundary conditions are:

\[
y(x = 0) = -c \tan \theta = -c \tan 25^{\circ} = -2.14129; \quad x(0) = b = \infty
\]

(5)
Using the governing Eq. (4) and boundary conditions Eq. (5), the height that the fluid can reach on the vertical wall is calculated to be 1.398372 mm, which agrees well with the experiment result of 1.40 mm. We used Matlab (MathWorks, Natick, MA) to solve this problem and plotted the result as shown in Fig. 5.

(2) Case 2: \( h \) is smaller than \( h_c (x = \infty) \), and \( b \) can be considered infinite. Hence the curvature of the meniscus is decided by \( h \). The boundary conditions are as follows.

\[
\dot{y}(x = 0) = -c \tan \theta = -c \tan 25^\circ = -2.14129; \\
y(0) = h\dot{y}(y = 0) = -c \tan \theta \leq -c \tan 65^\circ = -0.466038 \quad (6)
\]

In this case, the length of the fluid extended on the horizontal plane \( b_0 \) is dependent on the value of \( h \), namely, \( b_0 = f(h) \). The meniscus shapes with different \( h \) values were estimated by solving the governing Eq. (4) and the boundary conditions described in Eq. (6) using Matlab. The plotting results of different \( h \) values are shown in Fig. 6.

(3) Case 3: \( h \) is bigger than \( h_c (x = \infty) \) and \( b \) is smaller than \( b_0 \). Thus the curvature of the meniscus is decided by \( b \). The boundary conditions are as follows.

\[
\dot{y}(x = 0) = -c \tan \theta = -c \tan 25^\circ = -2.14129; \\
y(y = 0) = -c \tan \theta \leq -c \tan 65^\circ = -0.466038; \\
y(b) = 0 \quad (7)
\]
Based on the governing Eq. (4) and the boundary condition Eq. (7), the meniscus shapes can be computed in Matlab. Fig. 7 shows the plotting results for different b values.

(4) Case 4: h is smaller than \( h_l(x=\infty) \), and the length of the horizontal plane b is smaller than \( b_l \). Hence the curvature of the meniscus is decided by both b and h. The problem follows the boundary conditions:

\[ y(0) = h, \quad y(b) = 0 \]  

(8)

The meniscus shape can be calculated for different b and h values. Three examples using Matlab to solve the mathematic model and the related boundary conditions for different b and h values are shown in Fig. 8.

3. Process planning for building smooth up-facing surfaces

Suppose an input 3D CAD model with curved up-facing surfaces is given as shown in Fig. 9a. The traditional additive manufacturing method will slice the model into multiple 2D layers based on a given layer thickness. One mask image will be generated for each layer in the MIP-SL process to cure the related 2D shape. Consequently the built part will inevitably have stair-stepping defects.

In comparison, Fig. 9b illustrates the major steps of the meniscus equilibrium method for achieving smooth up-facing surfaces. For a specific layer \( i \), \( c(x, y) \) is computed which represents the ratio of the Z-height at the location \( (x, y) \) to the layer thickness \( L_l \). Similar to [14], a sliced image with gray scale values can be generated for each layer. Accordingly the thickness at pixel \( (x, y) \) is \( c(x, y) \times L_l \). Hence instead of a binary layer image, the sliced image has pixels with ratios \( c(x, y) \). Note \( c(x, y) \) is continuous and \( c(x, y) \in [0, 1] \). Suppose the original gray scale image can be split into two mask images, Images #1 and #2. As shown in Fig. 9b, the mask Image 1 can cure a portion of layer \( i \) that will be used in forming meniscus; the mask Image 2 can be used in curing the formed meniscus based on Image 1. Note that it is not necessary to use the meniscus equilibrium approach in building each layer. That is, depending on the given geometry, meniscuses can be formed by Image 2 after multiple layers of Image 1 have been built. This is different from the approach
presented in [15,16] for the SLA process, in which the formed meniscuses are cured in each layer. In addition to slow building speed, such an approach was found to only work for up-facing surfaces that are 40° or less from the horizontal. Such a limitation can be explained by the presented meniscus shape modeling.

As discussed in the meniscus mathematical model, two important parameters in determining the shape of the meniscus profile are \( h \) and \( b \). Thus the planning of Image 1 and Image 2 can change the setting of \( h \) and \( b \), which leads to different approximation errors between the meniscus profiles and the desired shapes. An illustration example is shown in Fig. 10a. For the given shape boundary defined by black lines, two different sets of mask images (Image 1 and Image 2) can be used, which define two vertical walls as shown in brown lines. Accordingly the formed meniscuses will have different profiles due to different \( b \) or \( h \) values as shown in Fig. 10a.

In order to generate the MIP-SL process plan that can ensure the meniscus shapes match the given curved geometry, the process planning for the up-facing surfaces can be mathematically defined. Both shape and curvature approximation errors need to be considered. The shape approximation errors \( \varepsilon_a \) can be computed by comparing the difference between the desired geometry profile \( f(x) \) and the meniscus profile \( F(x) \). The curvature approximation error \( \varepsilon_c \) can be computed by comparing the first derivative values of \( f(x) \) and \( F(x) \). Typically the profile is continuous within each meniscus while discontinuity may exist among neighboring meniscuses. Hence the goal in the process planning is to prepare a set of mask images such that the approximation errors can be minimized. Accordingly, the related problem can be formulated as follows:

**Input:** A curve surface \( f(x, h) \), a layer thickness, and goal preferences as weights \( W_1 \) and \( W_2 \).

**Find:** A set of \( b \) and \( h \)

**Satisfy:**

\[
\varepsilon_a,j = \int_{x_i}^{x_{i+1}} |f(x) - F(x)|dx \sum_{i=0}^{n} \nabla d_i(x_i);
\]

\[
\varepsilon_c,j = |F_1(x) - F_2(x)|;
\]

\[
b = \sum_{i} b_i; \quad h = \sum_{i} h_i.
\]

**Minimize:**

\[
W_1 \cdot \varepsilon_a,j + W_2 \cdot \varepsilon_c,j
\]

As shown in Fig. 10b, suppose a boundary curve \( y = f(x) (y \in (0, h), x \in (x_1, x_2)) \) is given. The input curve can be divided into several pieces such that \( h \) in the process planning is smaller than the maximum vertical height \( h_c \), as discussed in the meniscus model (Case 1). Suppose \( L_y \) is the layer thickness and a sampling distance \( e \) is used in computing the errors of the meniscus profile. An algorithm based on the greedy heuristic can be developed as follows. The meniscus shape in the area of \( y \in (0, h) \) is first estimated and compared with the input geometry. If the errors are within the acceptable ranges, \( P_n \) (i.e. point 3) can be selected as the meniscus point; otherwise, the meniscus shapes in the area of \( y \in (0, h - i \times L_y), i = 1, 2, \ldots \) are estimated until a meniscus point \( P_{n0} \) is found that satisfies the given approximation error ranges (e.g. point 1). The remaining curve can then be processed in a similar way to identify all the meniscus points \( P_{m0} \) (e.g. points 1–3). Based on the identified meniscus points, a set of projection images (Image 1 and Image 2) can then be computed for the building process. Accordingly Image 1 can be used

---

**Fig. 11.** The principle of the meniscus projection image calibration.
in solidifying resin in each layer. When the current layer number comes to \( h_i \) related to the meniscus point \( P_{hi} \), the fabricated model will be raised up from the liquid resin; after certain waiting time, related mask Image 2 will then be projected on the portion of the part surface to cure the formed meniscus shapes in such areas.

### 4. Meniscus projection image calibration and planning

As shown in Fig. 2, the built part is raised up above the liquid surface when the resin related to the desired meniscus shape is cured. Accordingly the mask image (Image 2) that will be used in the meniscus equilibrium approach needs to be planned by considering the distortions associated with the different Z heights of the desired meniscus shapes. Note the resin surface is the focus of the projection image. The formed meniscuses after lifting up for a certain \( Z \) height are actually out of focus. To identify a meniscus mask image with controlled exposure for all the meniscuses, the projection light modeling and calibration is first performed. Based on established pixel positions in the topmost and bottom planes, the inverse calculation of the mask image is presented for any given \( Z \) height. Hence the computed mask Image 2 will provide the desired projected light to exactly cover the portion of resin related to the meniscus shape that may located in different Z levels.

#### 4.1. Projection image modeling and calibration

The projection light of each pixel \((i, j)\) is assumed to be straight within the \( Z \) height range in which the formed meniscuses will be located. As shown in Fig. 11, if \( P_i(i, j) \) and \( P_2(i, j) \) on the top and bottom \( Z \) planes can be identified, the position \( P(i, j) \) for any given \( Z \) height can be easily computed based on the linear interpolation of \( P_1 \) and \( P_2 \). In this research, our projection image calibration method is based on the use of a high resolution camera (Canon SX10) to capture the relative position of a projected checkerboard and a physical checkerboard that is positioned at top and bottom \( Z \) levels. We then used image processing techniques to build a top and bottom \( Z \) level databases, in which, the physical positions of all the pixels on the two calibrated plane are recorded (refer to Fig. 12a). Based on them, a linear interpolation approach can be used in computing the physical position of a pixel in any given plane that is inside the calibration volume. Fig. 12b shows the calibrated databases in red and blue lines for the top and bottom layers considered in our setup, respectively. The projection results of some

---

**Fig. 12.** The meniscus projection image calibration result: (a) calibration data; and (b) a plot of the calibration result.

**Fig. 13.** An illustration of the meniscus image planning: (a) an input CAD model with related meniscus points; (b) the mask Image 2 of three sampling layers for curing formed meniscuses in related layers; (c) the mask images of the sampling layers after considering the distortion associated with different \( Z \) heights after raising up; (d) the projected mask Image 2 for curing the meniscuses formed in the first 20 layers.
intermediate Z levels were also processed, which verified the interpolation results.

4.2. Meniscus projection image planning

In the process planning results of a given CAD model, a set of mask Image 1 and Image 2 have been computed for each layer of the model (refer to Fig. 9). In addition, a set of meniscus points $P_{ni}$ have been determined. Based on them, the number of layers between two neighboring meniscus points and the related mask Image 2 for curing meniscuses related to all the layers are known. Accordingly, a single meniscus projection image can be computed by considering the distortion related to their Z heights. That is, since the platform will be moved upward for a certain height for forming meniscus, the mask Image 2 in each layer can be converted into a transformed image based on the aforementioned projection calibration results. Finally all the computed mask images can be combined to form a single projection image for the related meniscus points. Fig. 13 illustrates the mask Image 2 planning process based on an example similar to the test case as shown in Fig. 15. The CAD model of the test part is shown in Fig. 13a, which is sliced into 76 layers. The meniscus equilibrium method will be applied at layers 20, 40, 60, and 76. Based on the calibration results as shown in Fig. 12, the computed meniscus projection image for the first 20 layers (i.e. $P_{n1}$) is shown in Fig. 13d. The computing results of three individual layers (1st, 10th, and 20th) are also shown in the figure.

5. Experiment setup

A prototype system has been built for verifying the presented methods. The hardware setup of the developed MIP-SL system is shown in Fig. 14a. In the designed system, an off-the-shelf
projector (Acer H5360) was used as the projection device. The use of a commercial projector can significantly reduce the prototype cost and simplify the system design. The optical lenses of the projector were modified to reduce the projection distance. Various projection settings including focus, key stone rectification, brightness and contrast were adjusted to achieve a sharp projection image on the designed projection plane. The DMD resolution in our system is 1024 × 768 and the envelope size is set at 110 × 82 mm. Two linear motion stages from Thomson Industries Inc. (Radford, VA) are used in the system. One is used as the Z elevator for lifting the build platform; another is used as the sweeper for moving a blade to flatten the resin surface. A high performance 8-axis motion control board KFLOP+SnapAmp 1000 (Dynomotion Inc., Calabasas, CA) is used for driving the linear stages.

Commercially available photocurable resin (Perfactory SS500) was used in all the experiments. The exposure time was set at 3 s based on the curing depth analysis. A mask image planning and control software system has been developed by using the C++ programming language with Microsoft Visual C++ compiler. The graphical user interface (GUI) of the developed software system is shown in Fig. 14b. The system can load in a STL model, perform process planning and synchronize the mask image projection with desired linear stage motions. A set of test cases were designed to test the meniscus equilibrium method. The experimental results are presented as follows.

6. Results and discussions

6.1. Tests on straight up-facing surfaces

As shown in Fig. 15a, a CAD model with a slanted surface M was used in the test. To compare the differences between the traditional and the newly developed methods, the surface M was split into two halves, M1 and M2. The traditional method was used in building the upper half M1, and the meniscus equilibrium method was used in building the bottom half M2. The same layer thickness (0.1 mm) was used in the test. Accordingly a set of mask images was generated by slicing the given CAD model. However, one meniscus point every 10 layers was added in set \{M\} during the process of building M2. That is, after every 10 layers have been built, the built part will be raised up by a certain distance (above the resin surface by 1.5 mm). After waiting for several minutes, liquid will reach equilibrium. A mask Image 2 related to the portion of M2 within the built 10 layers is then projected to cure the formed meniscuses. The building result is shown in Fig. 15a. It is obvious that the appearance of the M2 portion is much smoother than that of the M1 portion.

Quantitative measurements have been performed to better understand the surface quality difference. The Z height of a set of uniformly sampled points on M was measured using a digital height gauge with a 0.1 mm probe tip. To automate the measuring process, two motion controlled linear stages from Velmex Inc. (Bloomfield,
NY) were used. In the measurement setup, the built part was fixed on a linear stage to be translated in the X direction. The digital height gauge was fixed on another linear stage to be translated in the Z direction. Every time the probe touches a sampling point on the surface, a height value will be recorded from the digital gauge. To avoid the friction between the probe tip and the slanted surface, the gauge moves away from M in the Z direction first before the part is translated by a small distance in the X direction. The recorded Z height values of the sampling points on surface M are plotted in Fig. 15b. The X axis denotes a set of uniformly spaced sampling points, where ‘0’ denotes the starting point of the measurement and ‘400’ denotes the 400th measuring point. The Z axis denotes the readouts from the digital height gauge. The recorded data of the upper half M₁ and the bottom half M₂ are plotted using blue and red points respectively. The quantitative comparison shows that the stair-stepping effect of M₁ is much greater than that of M₂. We also marked three portions, a₁, a₂, and a₃, on the surface as shown in Fig. 15b. They represent M₁, the transition between M₁ and M₂, and M₂ respectively. A precision measurement machine (Sol system from Micro Vu Inc., Windsor, CA) was used in taking microscopic images of these three portions. The captured images are shown in Fig. 15c. The results illustrate that the traditional method will lead to a ragged surface, while the meniscus equilibrium method can effectively eliminate the stair-stepping effect in the MIP-SL process.

6.2. Tests on curved up-facing surfaces – concave cases

As shown in Fig. 16a, a CAD model with a curved surface M was used in the test. The same process parameters were used in the traditional and the newly developed methods for building the CAD model. The related build results M₁ and M₂ are shown in Fig. 16a. The same measurement procedure as described in Section 6.1 was followed for a quantitative comparison of their surface finishes. The Z height values of the curved up-facing surface are shown in Fig. 16b. The same measurement procedure as described in Section 6.1 was followed for a quantitative comparison of their surface finishes. The Z height values of the curved up-facing surface are shown in Fig. 16b. The

6.3. Tests on curved up-facing surfaces – convex cases

As shown in Fig. 17a, a CAD model with a curved surface M was used in the test. The same process parameters were used in both the traditional and newly developed methods to build the model. The related build results M₁ and M₂ are shown in Fig. 17a. The same measurement procedure as described in Section 6.1 was followed for a quantitative comparison of their surface finishes. The Z height values of the curved up-facing surface are shown in Fig. 17b.
Table 1
Roughness of the built surfaces in Figs. 15–17.

<table>
<thead>
<tr>
<th>Figure</th>
<th>Surface</th>
<th>Roughness measures (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>( R_a )</td>
</tr>
<tr>
<td>Fig. 15</td>
<td>( M_1 ) (traditional)</td>
<td>0.028</td>
</tr>
<tr>
<td></td>
<td>( M_2 ) (meniscus)</td>
<td>0.010</td>
</tr>
<tr>
<td>Fig. 16</td>
<td>( M_1 ) (traditional)</td>
<td>0.031</td>
</tr>
<tr>
<td></td>
<td>( M_2 ) (meniscus)</td>
<td>0.008</td>
</tr>
<tr>
<td>Fig. 17</td>
<td>( M_1 ) (traditional)</td>
<td>0.027</td>
</tr>
<tr>
<td></td>
<td>( M_2 ) (meniscus)</td>
<td>0.012</td>
</tr>
</tbody>
</table>

microscopic images of a portion of \( M_1 \) and \( M_2 \) are shown in Fig. 17c. The test results verify the capability of the meniscus equilibrium method to fabricate smooth convex up-facing surfaces.

The profiles of the built surfaces were sampled with surface finishes measured. The computed roughness measures based on the traditional and the meniscus equilibrium methods are given in Table 1.

7. Conclusion

This paper presented a novel approach for building smooth curved surfaces in the mask-image-projection-based stereolithography process. A meniscus equilibrium method has been developed for building smooth up-facing surfaces. Based on the developed meniscus models in various scenarios, a process planning problem has been formulated. A solution strategy based on the greedy heuristic has been developed for the process planning of a given CAD model. A calibration and planning approach has also been developed for computing meniscus projection images that can accurately cure liquid resin in different \( Z \) heights. Experimental tests based on the developed method have been performed and compared with the traditional method. The differences in the build results illustrate the effectiveness of our method in improving the surface finish of curved surfaces in the MIP-SL process.

The presented method has demonstrated that it is possible to build smooth surfaces without using ultra-thin layers. As a proof-of-concept, the current development could be further improved in many avenues. We are exploring more advanced solution strategies for the formulated meniscus equilibrium problem to minimize the shape and curvature approximation errors in order to build up-facing surfaces with controllable shapes.

Acknowledgment

The authors acknowledge the support of ONR Grant N00014-11-1-0671.

References