Mask Image Planning for Deformation Control in Projection-Based Stereolithography Process

Kai Xu
Epstein Department of Industrial and Systems Engineering, University of Southern California, Los Angeles, CA 90089

Yong Chen
Epstein Department of Industrial and Systems Engineering, University of Southern California, Los Angeles, CA 90089
e-mail: yongchen@usc.edu

The mask-image-projection-based stereolithography process (MIP-SL) using a digital micromirror device (DMD) is an area-processing-based additive manufacturing (AM) process. In the MIP-SL process, a set of mask images are dynamically projected onto a resin surface to selectively cure liquid resin into layers of an object. Consequently, the MIP-SL process can be faster with a lower cost than the laser-based stereolithography apparatus (SLA) process. Currently an increasing number of companies are developing low-cost 3D printers based on the MIP-SL process. However, current commercially available MIP-SL systems are mostly based on Acrylate resins, which have larger shrinkages when compared to epoxy resins used in the laser-based SLA process. Consequently, controlling the shrinkage-related shape deformation in the MIP-SL process is challenging. In this research, we evaluate different mask image exposing strategies for building part layers and their effects on the deformation control in the MIP-SL process. Accordingly, a mask image planning method and related algorithms have been developed for a given computer-aided design (CAD) model. The planned mask images have been tested by using a commercial MIP-SL machine. The experimental results illustrate that our method can effectively reduce the deformation by as much as 32%. A discussion on the advantages and disadvantages of the mask image planning method and future research directions are also presented. [DOI: 10.1115/1.4029802]

Keywords: additive manufacturing, mask image planning, deformation control, stereolithography, mask image pattern

1 Introduction

The layer-based AM processes can directly build physical objects based on three-dimensional (3D) CAD models (e.g., STL files). SLA is one of the most commonly used AM processes. In the SLA process, a 3D CAD model is first sliced into a set of 2D layers. The 2D layers are then processed by the computer for controlling the tool path of the laser beam such that parts are fabricated by selectively curing liquid resin into solid [1]. As it happens in other manufacturing processes such as injection molding and casting, solidifying liquid resin in the SLA process undergoes shrinkage. When liquid resin is exposed to ultraviolet (UV) light over certain energy, the photopolymerization process will start such that small monomers are linked into large polymer molecules. Such a process will cause volumetric shrinkage and temperature increase. However, note that the cured layers are constrained by its supports or the previously built layers. Hence residue stress will accumulate in the built part, which will lead to curl distortion after all the supports are removed [2].

Extensive research has been performed to identify the key building parameters in the SLA process that can influence part shrinkage. Accordingly, many build styles based on different laser beam scanning patterns have been developed and used in the commercial machines from 3D Systems Inc. (Rock Hill, SC). Typically, the build styles can be put into two categories: straight (or noncyclic) and cyclic build styles [3]. Different scanning methods (or build styles) can result in varying building speed and accuracy of final parts. Research on tool path planning in AM processes has been reported for building accurate part and features [4–6]. In addition, photopolymerization models and related simulation methods have been developed to predict the shrinkage-related deformations. For example, Huang and Lan [7] used dynamic finite element method to simulate the laser beam scanning process which scans along the x direction in odd layers and along the y direction in even layers. Later, they investigated the influence of three types of path scanning [8]. Campanelli et al. [9] employed the Taguchi method to study the effect of hatchling style parameters in fabricated parts in order to find a combination with the best accuracy. Narahara et al. [10] analyzed the relation between the laser scanning and linear shrinkage of a single strand using experimental equipments developed by them. Simulation study of curl distortion due to laser scanning was also performed [2,11]. Similar simulation modeling research has been conducted in other AM processes as well [12–14].

Digital devices such as liquid crystal display and DMD provide the capability of dynamically controlling the energy input of an area. The use of such devices in developing novel AM processes has been recognized as an important direction. The basic idea of the mask-image-projection-based stereolithography (MIP-SL) process is to use a set of mask images to cure part layers [15–23]. The MIP-SL process is illustrated in Fig. 1(a). In such a process, the building speed can be greatly improved since a whole layer can be cured by a single exposure. Several mask image planning methods have been developed for the MIP-SL process before [24–27]. In addition, previous work on accuracy modeling and deformation analysis has been performed [28–31].

Two types of photopolymer systems, acrylate chemistry and cationic photopolymerization, are used in the SLA process [1]. Acrylate chemistry polymerizes via a free-radical mechanism while cationic photopolymerization undergoes ring-opening reactions in the presence of cationic photoinitiators. Epoxy resin, the
in this paper is to design the mask images used in the building
the shrinkage-related shape deformation. The approach considered
Another way is to modify the input CAD model to compensate for
the shrinkage is to develop a liquid resin that has less shrinkage.
For example, one effective way of reducing
the MIP-SL process. For example, one effective way of reducing
process and can be cured by both UV and visible light. However,
acrylate resin has larger shrinkage than epoxy resin [32]. Conse-
sequently, the deformation control in the acrylate-based MIP-SL
process is more challenging than the epoxy-based SLA process. In
order to fully utilize the benefits of the MIP-SL process such as
fast building speed and low machine cost, it is critical to address
the shrinkage-related shape deformation problem in the MIP-SL
process.

In this paper, a mask image planning method is presented for
reducing the shrinkage-related deformation in the MIP-SL pro-
cess. As shown in Fig. 1(b), the basic idea of our approach is to
generate different exposure mask patterns for each layer, which is
similar to the build styles that have been developed for the laser-
based SLA process. Even though a lot of research has been done
for the scanning-based SLA process, we did not find literatures on
similar effort for the projection-based SLA process. We believe
identifying appropriate mask image exposure strategies is impor-
tant for the MIP-SL process. Three different exposure strategies
have been studied in our research. The related mask patterns, as
well as their defining parameters, are characterized. Based on
them, more exposure strategies can be generated by exploiting the
possible combinations of the defining parameters in each pattern.
A software system has been developed that can plan mask images
with desired mask patterns for a given CAD model. Two test cases
have been designed to verify the presented mask image exposure
strategies. Statistical analysis has been applied to identify the
most significant parameters in the explored exposure strategies.
The experimental results demonstrate the effect of using the
designed exposure strategies in achieving improved accuracy of
built parts.

2 Mask Image Planning of MIP-SL

There are several possible ways for reducing the shrinkage in
the MIP-SL process. For example, one effective way of reducing
the shrinkage is to develop a liquid resin that has less shrinkage.
Another way is to modify the input CAD model to compensate for
the shrinkage-related shape deformation. The approach considered
in this paper is to design the mask images used in the building
process such that the built objects will have less shape deforma-
tion. A simple example to illustrate our approach is given in
Fig. 2.

For a given CAD model as shown in Fig. 2(a), a slicing plane
related to the model is shown in Fig. 2(b). The mask image of the
sliced layer is shown in Fig. 2(c). Currently most MIP-SL systems
[15–27] directly use such a mask image in building the related
layer. Since no designed exposure strategy is used, the shrinkage
of the layer is large especially for a large projection area. Alterna-
tively, one exposure strategy is to use a solid boundary with
square patterns to cure the layer (refer to Fig. 2(d)). For such a
projection image, all the cured areas are small and, more impor-
tantly, separated. Consequently, the shrinkage would be much
smaller. This is similar to the use of a set of scanning vectors
instead of filling vectors in the laser-based SLA process to cure
each layer in order to reduce part shrinkage. Another exposure
strategy that we can learn from the laser-based SLA process is to
project the internal portions first (refer to Fig. 2(e)). After the
internal portions have been cured, a mask image related to the
layer boundary can then be projected to define the final shape of
the layer (refer to Fig. 2(f)), which is similar to the border vectors
in the laser-based SLA process. Such a strategy is called
“boundary exposure last.” In this paper, we will first discuss the
principle of setting mask image patterns in Sec. 2.1. Our tempera-
ture study of different mask image patterns is presented in
Sec. 2.2. Finally, the steps of creating mask pattern exposure stra-
gies are summarized in Sec. 2.3.

2.1 Principle of the Pattern-Based Mask Image Planning
Method. To reduce the part deformation in the MIP-SL process,
the approach of alternatively exposing different cross-sectional
regions (or the volume) of the part in each layer is explored. As
demonstrated in the laser-based SLA process, the larger the cross-
sectional region is, the more shrinkage it will have due to the fac-
tors such as the density difference between solid and liquid. The
internal stress will also be generated due to the temperature
increase in the polymerization process and the cool down process
afterward. Thus, instead of curing the whole layer in one expo-
sure, an alternative curing strategy is to use designed mask pat-
tterns in the projection images, that is, to decompose the expo-
sure of a large area in one layer into several exposures of smaller
areas in multiple layers. When all these smaller regions are cured,
the whole volume of the CAD model will be cured without leav-
ing any voids that are uncured. Figure 3 presents a simple example
to illustrate the idea. Note that overcure is required in the MIP-SL process in order for a newly cured layer to bond with previous layers. An appropriate projection time can be set to ensure an exposed image at current layer $i$ will also cure the resins at the same position in the previous few layers (e.g., 4 layers as shown in Fig. 3). Such small regions are denoted as exposure mask patterns in this research.

To develop an effective exposure strategy, it is desired to understand how the exposure of a large region can be decomposed into multiple exposures of smaller regions. As shown in Fig. 3, suppose a cube whose cross-sectional region is $A$ needs to be cured. The cube has many layers with the same shape in each layer. If no exposure mask patterns are applied, the same mask image $A$ will be exposed in building each layer with an overcure of two layers. However, when adopting a mask-pattern-based exposure strategy, only $1/4$ of the cube can be exposed in each of the four layers. That is, $A_1$ can be exposed in the first layer, $A_2$ in the second layer, $A_3$ in the third layer, and $A_4$ in the fourth layer. The patterns will be repeated for the remaining layers. Note that the exposure of $A_2$ in the second layer will overcure the region $A_2$ in both first and second layers (i.e., light will penetrate several layers down). Similarly the exposure of $A_1$ and $A_4$ will cure the related regions in the bottom layers. Hence the whole volume of the cube will be cured after iteratively exposing these four mask patterns. For the layers that are related to the top surface of the cube, the whole projection region ($A$) will still be used to ensure the external surfaces of the cube will be completely cured. A tradeoff of the new exposure strategy is that it may require longer exposure time due to the larger overcure that is required.

**2.2 Curing Temperature Study of the Pattern-Based Mask Image Exposures.** There are two main reasons that may lead to the shape deformation in the MIP-SL process [11,29]. One is the volumetric shrinkage, which comes from the phase change of material from liquid monomer to solid polymer. Another reason is the thermal cooling effect. It is well known that SLA is an exothermic process, that is, the heat generated in the curing process may lead to temperature rise in the built layers. The layers will then shrink when they cool down. A designed pattern exposure strategy can be effective in reducing shape deformation by alternatively exposing discrete small regions instead of the entire volume.
in the electron beam additive manufacturing process [33, 34]. The sensors have been used in measuring the build surface temperature real-time temperature changes of a curing region. Similar thermal (ThermoVision SC8000, FLIR System) is used in recording the sure strategies, a calibrated high-resolution infrared (IR) camera terns on the curing temperature of a layer. It is desired to understand the effect of the used mask pat-

To study the curing temperature of using different image exposure strategies, a calibrated high-resolution infrared (IR) camera (ThermoVision SC8000, FLIR System) is used in recording the real-time temperature changes of a curing region. Similar thermal sensors have been used in measuring the build surface temperature in the electron beam additive manufacturing process [33, 34]. The IR camera can detect temperature changes that are as small as 25 mK [35]. The IR camera is calibrated before it is used for the temperature measurement. In the process of calibration, the IR camera takes a number of blackbody measurements at several known reference temperatures. As shown in Fig. 4, a setup based on the free-surface-based MIP-SL process is used to facilitate the IR camera measurement. The IR camera is fixed on a tripod with a proper view of the curing region. During the building process, real-time temperature readings of the curing regions are recorded and transferred to a computer that is connected to the IR camera.

A simple rectangular layer with length 60 mm and width 5 mm is designed to investigate the curing temperature differences by using different pattern exposure strategies (refer to Fig. 5(a)). The mask image of a sliced layer is shown in Fig. 5(b). The four mask patterns, designed based on the method as described in Fig. 3, are shown in Fig. 5(c). The size of small cured region is 8 × 8 pixels (each pixel is 0.12 mm).

Physical experiments have been designed to investigate the maximum mean temperature within the curing region. The layer thickness is set at 0.127 mm. In the first experiment, the mask image as shown in Fig. 5(b) was used to cure the layer. The IR camera records the evolution of the temperature within the curing region. Two more experiments are carried out by using the mask pattern exposure strategy as shown in Fig. 5(c). In the second experiment, the four patterns are applied consequently in four continuous layers. The exposure time of each layer is two times longer than the first experiment for a larger overcure. In the third experiment, all the four patterns are applied consequently in one layer for curing the entire region. The same exposure time of each pattern is the same as the one used in the first experiment. The}

Figure 6(a) shows the curing temperature evolution within the entire exposing region (denoted by top curve) when applying the mask image shown in Fig. 5(b). The maximum mean temperature within the curing region is ~28.6°C, while the liquid resin temperature, measured outside the curing region, is about 25°C (denoted by bottom curve). Hence the difference between the curing temperature and liquid resin temperature is ~3.6°C. In Fig. 6(b), the four peaks in top curve represent the maximum temperature when applying four mask patterns iteratively in four continuous layers. The temperature measurements show the maximum temperature in a curing layer is ~27°C, which is approximately 2.4°C higher than the liquid resin temperature. Figure 6(c) shows the temperature evolution of curing a layer when applying four patterns in one layer. The maximum temperature is around 24.9°C, which is about 1.2°C higher than the liquid resin temperature. It must be noted that the three experiments were conducted in different time within a day. The slight difference in the measured liquid resin temperatures in the experiments may be due to the room temperature variation. The IR temperature study shows that different mask pattern exposure strategies will lead to varying temperature increases within the curing layer. The current practice of using the mask image of a sliced layer has a large temperature increase. However, a lower temperature increase may be beneficial since less thermal shrinkage will be generated when the layer is cooled down. Consequently, the build object will have less shape deformation.

In summary, a designed mask-pattern-based exposure strategy can be effective in the MIP-SL process because: (1) the cured small regions will have less shrinkage; (2) the generated internal stress in one region will have little effect on other regions since all the small regions are disconnected; and (3) the curing temperature within the curing region will be lower. However, a significant disadvantage of using the presented exposure strategies is the longer building time. For example, compared to the first experiment (i.e., without using any mask patterns), the building time in the second and third experiments is two times and four times longer, respectively. It is desired to develop different exposure strategies for the MIP-SL process such that a user can select one based on his/her preference between building time and part quality. In the remaining of the paper, the exposure strategy related to the second experiment will be further studied due to its good balance between the building time and the shape deformation.

2.3 Overview of the Pattern-Based Mask Image Planning Method. The steps for decomposing the exposure of a larger region into multiple smaller regions can be summarized as follows:

(1) Suppose the internal area of a large region to be exposed in a layer is $A_{\text{Internal}}$ and the maximum overcure layer number is $N (N > 1)$.

(2) For the $i$th layer ($1 \leq i \leq M, M \leq N$), design the mask pattern such that the area related to the designed pattern shapes are $A_{\text{Internal},i}$.

![Fig. 5 An illustration of test layer and mask patterns. (a) Dimension of a test layer; (b) the mask image of the test layer; and (c) four designed mask patterns of the test layer.](image)
(3) When building these $M$ layers, $A_{\text{Internal}}$ and $A_{\text{Internal, i}}$ must satisfy: $A_{\text{Internal}} = (\bigcup_{i=1}^{M} A_{\text{Internal, i}})$ such that the area of $A_{\text{Internal}}$ can be cured. If not, the designed patterns in these $M$ layers may lead to uncured volume.

(4) The designed patterns are iteratively used for the internal volume of the object to ensure all the layers will be properly cured.

Note that the mask patterns should only be applied to the internal volumes of an object. They should not be used for the part boundary since multiple exposures on the part boundary will adversely affect its surface quality. Consequently, the boundary and internal portions of an object need to be separated in order to perform the related mask image planning for them. Suppose a given CAD model is denoted as $S$ and a boundary distance is given as $r$. Offsetting $S$ by $r$ into a grown or shrunken version of $S$ has been precisely defined for point sets in Euclidean space $E^2$ or $E^3$ [36]. Suppose $S$ shrunk by $r$ is defined as $S_r$. Accordingly the internal volume of $S$ is $I(S) = S_r$, (refer to Fig. 7). The part boundary of $S$ is $B(S) = S - I(S)$, where “$-$” is the subtraction between the two models. In our study, the offsetting method [36] is used in computing $B(S)$ and $I(S)$ for a given CAD model. Accordingly, all the pixels in a sliced image can be classified into boundary pixels and internal pixels, and the mask patterns will only be applied to the internal pixels.

Since only the internal volume of an object based on a given $r$ will be applied with the mask patterns, neither the part boundaries (both in the $XY$ and $Z$ directions) nor small features will be affected by the discussed mask-pattern-based exposure strategy. This is further explained as follows.

(1) In addition to the part boundary in the $XY$ axis (refer to an example in Fig. 2(e)), the part boundary in the $Z$ axis will be fully exposed without applying the mask patterns. Figure 8 shows some layer examples based on the CAD model as shown in Fig. 2(a). For the slicing layers that are adjacent to the planes of $A$, $B$, and $C$, the related mask images after applying the square mask patterns are shown in the figure. Note that the pixels that are related to the part boundary $B(S)$ are fully exposed. This can ensure the built object will not have any uncured regions on its boundary.

(2) For a given boundary distance $r$, any features that are smaller than a circle with the radius $r$ will not have any internal volume. Hence such features will be fully exposed without considering any mask patterns. A small region is typically not problematic for shape deformation since the related shrinkages are quite small. Applying mask patterns
sizes can be defined in the isolated cube pattern. The pattern shape deformation in the MIP-SL process are presented in Sec. 5. Detail definitions of the three mask patterns and the related exposure patterns, which will be investigated in our future work.

surface-connection, volume-connection, and line-connection, which may exist between the subdivided regions, i.e., region. These three exposure patterns represent the three connection types that may exist between the subdivided regions, i.e., surface-connection, volume-connection, and line-connection, respectively. For each connection type, there may be some other exposure patterns, which will be investigated in our future work. Detail definitions of the three mask patterns and the related parameters are described as follows. Their effects on reducing the shape deformation in the MIP-SL process are presented in Sec. 5.

3 Design of Exposure Patterns and Parameters

Many exposure patterns can be defined as long as the criteria as described in Sec. 2.3 are satisfied. In this research, three types of exposure patterns based on the potential topology connections of small regions are designed. As shown in Fig. 10, the first exposure pattern is designated as an isolated cube pattern, in which a large rectangular region is decomposed into four cubes. The second exposure pattern is designated as a loop structure pattern, in which several loops are used to form a large rectangular region. The third exposure pattern is called a weave structure pattern, in which a set of grid lines are used to cover a large rectangular region. A weave structure region is cured in each layer; and four types of exposure patterns based on a hybrid approach will be further investigated in our future work.

3.1 Isolated Cube Pattern

Isolated squares with different sizes can be defined in the isolated cube pattern. The pattern description is shown in Fig. 11(a), in which the notation “#” denotes the area to be cured, while “0” denotes the area that will not be cured. One of the main parameters of the isolated cube pattern is the gap size, which defines the size (in pixels) between two neighboring small cured regions in both the X and Y axes. In our study we assign the same value by assuming it is symmetry along the two directions. An example of a mask image based on the gap sizes of 5 and 8 pixels are given in Figs. 11(b) and 11(c), respectively. Both examples use a pattern size of 32 x 32 pixels.

Suppose the iteration number of the isolated cube pattern (N) is 4. Four consecutive layers (i, ..., i + 3) need to be exposed in order for the whole region of a current layer i is cured (refer to Fig. 3). An example of four mask projection images using the isolated cube pattern is shown in Fig. 5. If each of the four exposure patterns is applied twice for two neighboring layers, the iteration number of the isolated cube pattern will be eight since the four mask patterns will be applied for eight continuous layers. The defined iteration number also applies to other types of exposure patterns.

3.2 Loop Structure Pattern

The pattern definition of a loop structure pattern is shown in Fig. 12. Parameters a, b, c, and d describe the sizes of cured loops in each exposure. For a pattern size of 32 x 32 pixels, the loop structure pattern based on a = 8, b = 8, c = 8, and d = 8 is shown. The parameters define the number of pixels in a row and in a column of the cured area in the mask patterns. An example of applying the defined loop structure pattern for a cube is shown in Fig. 12(b).

3.3 Weave Structure Pattern

Figure 13 shows the definition of a weave structure pattern. In the exposure pattern, a weave-structure region is cured in each layer; and four types of weave structures are shifted to different portions of a region. For the defined weave structure pattern, a parameter denoted as gap size is adopted to characterize the pattern design. The gap size is defined as the number of pixels in the X and Y axes of uncured square area. A gap size of eight is defined for the weave structure pattern as shown in Fig. 13. A mask image example based on the defined weave structure pattern is shown in Fig. 10(c).

4 Experimental Setup for the Pattern-Based Mask Image Planning Study

4.1 Software System for the Mask Image Planning

As shown in Fig. 1(b), a software system will slice a given CAD
model into a set of 2D layers using a given layer thickness. Based on the specified exposure mask patterns as discussed in Sec. 3, a set of modified 2D mask images will be automatically generated. The mask images and the related building parameters will then be sent to the MIP-SL machine. The physical object is built after all the 2D layers have been cured. Finally, the shape deformation of the fabricated part is measured in order to understand the effects of the used mask patterns and related parameters.

The slicing of a 3D model $S$ into a set of 2D layers has been well studied before. Based on the sliced image, a mask pattern should only be applied to the internal pixels defined by a given thickness $r$. In our study, a 3D offsetting operation based on the layered depth-normal images [36] is used to compute the CAD model of $S_r$. The generated model $S_r$ is sliced using the same layer thickness. Accordingly, the inner and boundary pixels of $S$ can be easily identified. As discussed in Sec. 2.3, the defined mask patterns will only be used in modifying the internal pixels while the boundary pixels will not be changed.

Figure 14 shows the algorithm for adding desired exposure patterns in the sliced layers of a given CAD model. For each layer to
Fig. 14 Algorithm of exposure mask pattern generating program

be processed, the algorithm will also check whether the layer will use the exposure strategy of boundary exposure last. That is, the inner regions can be cured first before the part boundary is to be cured (refer to an example in Figs. 2(e) and 2(f)). This is similar to the scanning strategy adopted in the laser-based SLA process by using hatching vectors before applying border vectors in the end. Accordingly, the MIP-SL system will expose the resin surface twice when building the layer. A side effect of using boundary exposure last is that the building process will be longer compared to projecting a mask image that combines both boundary and inner pixels.

A mask image planning software system has been developed using C++ programming language with Microsoft Visual C++ 2005. The program can automatically generate 2D mask images with different exposure patterns for a given 3D model. Desired exposure mask patterns is defined as a set of text files as shown in Figs. 11–13. Besides mask patterns, a user can also specify the boundary thickness, the layer range to apply the mask patterns, and whether to use boundary exposure last, etc.

4.2 Hardware System and Experimental Procedure. A commercially available MIP-SL system (the ULTRA machine [23] from EnvisionTEC) is used in the physical experiments. The ULTRA machine accepts mask images that are defined as BMP or PNG files. For each mask image, a related exposure time needs to be specified. In this research, experiments based on the three exposure mask patterns as described in Sec. 3 are conducted to verify the effectiveness of applying mask pattern exposure strategy on reducing shape deformation. The experimental procedure is described as follows. First, a benchmark test part is fabricated without any exposure mask pattern. The part will be served as a control group. Then, test parts by applying different exposure strategies and related defining parameters are built. In addition, the effect of setting boundary exposure last is also investigated. In our study, the thickness $r$ to define boundary pixels is set at 0.45 mm (3 pixels).

The following patterns and combinations of parameters are studied in our experiments. (1) In the isolated cube structure pattern, experiments with the combinations of following parameter values are considered: $\text{gap size} = 5$, 6, 7, or 8 pixels, $\text{iteration number} = 4$, 8, or 12, and with or without boundary exposure last. (2) In the loop structure pattern, experiments are conducted with the combinations of the following parameter values: $a = b = c = d = 8$ pixels, and $a = 12$, $b = c = 8$, $d = 4$ pixels, $\text{iteration number} = 4$, and with or without boundary exposure last. (3) In the weave structure pattern, experiments are conducted with the combinations of the following parameter values: $\text{gap size} = 8$, $\text{iteration number} = 4$, or 8, and with or without boundary exposure last. Due to the cost of the experiments, a design of experiment approach based on a full factorial design is applied to the parameter combinations in these experiments to investigate their effects.

5 Experiment Results and Discussions

5.1 Test Case 1. A rectangular bar is used to verify the effectiveness of the proposed mask pattern exposure strategy. A built test part is shown in Fig. 15(a). Its size is 60 mm in length, 5 mm in width, and 2.6 mm in thickness. A support structure of 1.6 mm height is added below the test part. During the building process, the cured layer will shrink. However, the shrinkage movement is restricted by the bottom supports and the underlying layers that have been built. Consequently, residual stresses will be accumulated in the built object. After the part is built and removed from the supports, the residual stresses will be released, which leads to the curl distortion (refer to the two tips A and B in Fig. 15(a)). The curl distortion of a built part is measured using a precision measuring machine from Micro-Vu Inc. (Windsor, CA) [37]. Figure 15(b) shows the schematic of the measurements. The distance $e$ is denoted as the curl distortion of the part in our study. Ideally, $e$ is zero if no curl distortion exists.

Test parts with and without a pattern exposure strategy are built using the MIP-SL machine. The tested pattern exposure strategy is based on the isolated cube structure pattern using the parameters: $\text{gap size} = 8$ pixels, iteration number 4 and with boundary exposure last. A layer thickness of 0.05 mm is used for all the test parts. Three replicates for both settings have been built. The same procedure is used in building the test parts. After finishing the building process, the test parts are removed from the platform. The supports are then removed and the parts are cleaned. The curl distortion $e$ of the test parts is measured. The measured curl distortion values are shown in Table 1. The average distortion for the
baseline part (i.e., without using any mask patterns) is 0.38 mm. In comparison, the test parts using the proposed isolated cube patterns have an average curl distortion of 0.26 mm. This represents an improvement of 31.6%.

5.2 Test Case 2. A benchmark part is designed to study the effectiveness of different exposure strategy and related parameter combinations in improving the shape deformation. The designed test part is similar to “letter-H,” which has been widely used in the SLA accuracy study [38]. The 3D model of the designed part is shown in Fig. 16(a). Its 2D sketch with related dimensions is shown in Fig. 16(b).

Appropriate support structures are added under plate A in order for the MIP-SL process to build the part. The base is positioned on a XY plane and the layer building direction is along the Z axis. As shown in Fig. 16(a), the shrinkage of plate A will lead to the two side walls deform. Dents on each side wall (refer to points A and B) will be generated when the two side walls are pulled inwardly. The length of \( AB \) can be measured in the built parts. By comparing the measured length with the nominal value of 101.6 mm, the shrinkage of plate A during the building process can be evaluated.

Different mask pattern exposure strategies can be used in building plate A. The shape deformation is reduced if the measured length \( AB \) in the built part is closer to the nominal value. The total number of sliced layers in the benchmark part is 508. The number of layers to be processed with different mask patterns is 51 (related to the layers of plate A). After finishing the building of a test part with specified mask patterns, the built object is taken out from the platform and the postprocessing including removing supports and cleaning the part are performed. Afterward, the length of \( AB \) is measured using the Micro-Vu precision measuring machine. The resolution of the used measuring machine is 1 \( \mu m \). The measured result is saved and compared with the nominal length.

5.2.1 Experiment Results. Table 2 shows the measurement result of the benchmark test part without applying any exposure mask patterns. Three measurements are performed for each built part. The mean value and standard deviation of the measurements are calculated. In the table, absolute shrinkage (Error) is defined as Error = \( L_{\text{nominal}} - L_{\text{mean}} \), and the shrinkage rate (Error%) is defined as Error\% = \( \frac{L_{\text{nominal}} - L_{\text{mean}}}{L_{\text{nominal}}} \times 100 \), where \( L_{\text{nominal}} \) is the nominal dimension of length \( AB \) (i.e., 101.6 mm), \( L_{\text{mean}} \) is its corresponding calculated mean dimension using the three measurements.

The test parts by applying different exposure patterns have undergone the same building and postprocessing steps. The built objects have also been measured using the same procedure. Table 3 shows their shrinkage results compared to the benchmark part. The shrinkage improvement is calculated by Error\%benchmark/\( Error\%_{\text{patterns}} \times 100 \), where Error\%benchmark is the shrinkage rate of the benchmark part, and Error\%patterns is the shrinkage rate of a test part using a designed exposure pattern.

5.2.2 Results and Discussions. For the isolated cube exposure pattern, a bigger gap size leads to better shrinkage improvement. Figure 17 shows the test parts for different gap sizes using the same exposure parameters (pattern size 32 × 32, iteration number of 8 and with boundary exposure last). Another parameter is the iteration number. Figures 18 shows the effect of Iteration Number on test parts using gap size of 8 pixels. When iteration number increases from 4 to 8, the shrinkage rate decreases.

For the loop structure exposure pattern, the test parts using pattern size of \( a = b = c = d = 8 \) pixels have better shrinkage improvement than those using pattern size of \( a = 12, b = c = 8, d = 4 \) pixels. For the pattern size of \( a = b = c = d = 8 \) pixels, no obvious differences exist when the boundary exposure last is applied; however, for the pattern size of \( a = 12, b = c = 8, d = 4 \) pixels, the test parts using the boundary exposure last strategy have less shrinkage than the ones without it.

For the weave structure exposure pattern, two test parts using gap size = 8, iteration number = 4 and 8, and without boundary exposure last have been built. The results show that no obvious shrinkage improvement is observed. Hence, no further experiments with other parameter settings have been performed for the weave structure exposure patterns.

As shown in Table 3, the test parts using the isolated cube exposure patterns generally have better improvements on reducing shrinkage than the test parts using the loop structure and the weave structure patterns. This is mainly because the connections between cured regions in each layer are different. In the isolated cube pattern, each cured regions are isolated. Hence less connection exists between neighboring cured cubes. However, in the loop structure and weave structure patterns, cured regions are more connected to each other. Hence the shrinkage on one cured region may affect other regions, which leads to bigger shrinkage in built objects.

In order to understand which factors are more significant in the isolated structure pattern, the full factorial design method is applied to analyze the measured data. As stated before, the shrinkage of plate A can cause the length of \( AB \) to be smaller than the
nominal size. The dimension of $AB$ is chosen as the response in our experiments. The three factors that are considered are the gap size between squares ($A$), pattern iteration number ($B$), and whether to use boundary exposure last ($C$). Each factor has two levels: gap size is 7 or 8 pixels, iteration number is 4 or 8, and boundary exposure is 0 (no) or 1 (yes).

The purpose of the full factorial design experiment is to find the optimal factors and the levels that can move the response closer to the nominal value with a variation that is as small as possible. Each treatment is run for three times. The data are shown in Table 4, in which $y$ is the average of the response, while $\ln S^2$ is the natural logarithm of sample variance of the response. A statistical software JMP from SAS Institute Inc. (Cary, NC) is used to do the 2$^3$ full factorial design analysis. According to JMP, the factorial estimated contrasts are shown in Table 5. Based on the analysis, main factors $A$ and $B$ are significant factors in location model, while factor $ABC$ is significant in dispersion model.

The following regression equations are generated based on the data in Table 5 (let $z = \ln S^2$: $\hat{y} = 99.672 + 0.12922x_A + 0.06974x_B$, and $\hat{z} = -9.375 - 0.6798x_Ax_C$. The recommended level for $ABC$ is the +1 to reduce the variance. In order to move $\hat{y}$ close to 101.6, levels $x_A = 1, x_B = 1$ are chosen by approximating the equation: $99.672 + 0.12922x_A + 0.06974x_B = 101.6$, and $x_C = 1$. Hence, the recommended settings are gap size is 8, iteration number is 8, and using boundary exposure last.
The statistical analysis result is consistent with the physical experiment results. As shown in Table 3, the exposure strategy based on the isolated cube pattern with parameters of gap size = 8, and iteration number = 8 generally leads to the best shrinkage improvement. The setting of boundary exposure last leads to a small difference (30.7% versus 32.3% improvement compared to the benchmark test part).

A comparison of the built parts based on two different exposure strategies is shown in Fig. 19. A photo of the benchmark part without using any exposure mask patterns is shown in Fig. 19(a); a photo of the built part based on the aforementioned recommended settings is shown Fig. 19(b). The differences of the dents generated in A and B points can easily be observed in the built objects.

6 Conclusion and Future Work

The shrinkage-related shape deformation is a major challenge in the MIP-SL process. To improve the accuracy of a built object, a mask image planning method based on applying designed mask patterns to the internal volume of a built object has been presented. The related mask image generating algorithm has also been developed for a given CAD model. The curing temperature study verifies that curing multiple small volumes in a single or multiple layers can reduce the temperature increase during the building process. Three types of mask patterns have been investigated including the isolated cube, loop structure, and weave structure patterns. Among them, the isolated cube pattern generally leads to a smaller shape deformation compared to the other two types of mask patterns. A full factorial design method has also been used in studying the significant factors and levels of the isolated cube pattern in order to identify the parameters to achieve the best shape deformation improvement.

Our future work includes: (1) performing more physical experiments for the isolated cube pattern to better understand the effects of related parameters; (2) investigating more mask pattern exposure strategies including the mask patterns that may have longer build time; and (3) developing a simulation system that can predict the shape deformation based on different building parameters.

Acknowledgment

The work was partially supported by the ONR Grant No. 0014-11-1-0671. We also acknowledge the support of EnvisionTec Inc. and the help of Prof. Qiang Huang at USC.

References


