A Fast Mask Projection Stereolithography Process for Fabricating Digital Models in Minutes

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1 Introduction

Layer-based additive manufacturing (AM) processes, such as stereolithography apparatus (SLA), can fabricate parts directly from computer-aided design (CAD) models without part-specific tooling or fixtures. As a direct manufacturing approach, AM processes can cost-effectively fabricate truly complex three-dimensional (3D) shapes that were previously impossible. Unlike traditional prototyping approaches that take days, AM-based rapid prototyping can build physical objects in hours. Due to such time and cost benefits, AM processes have been widely adopted in the product development process for building prototypes of a design.

Although the speed of AM systems has significantly increased over the years, the building process of a moderate sized 3D model is typically measured in hours. In a recent NSF workshop on developing the roadmap for AM [1], the development of AM machines with higher throughput was identified to be critical for future rapid manufacturing requirements. Future high-speed AM systems require new approaches, evolving from point-processing or line-processing methods, such as a laser or an extruding nozzle, to area-processing or volume-processing methods.

In this research, we investigate the building speed of an area-processing approach that is based on a DMD. A DMD is a microelectromechanical system device that enables one to simultaneously control ~1 million small mirrors that turn on or off a pixel at over 5 KHz. Using this technology, a light projection device can project a dynamically defined mask image onto a resin surface to selectively cure liquid photopolymer resin. In order to achieve high-speed fabrication, we investigate the bottom-up projection system in the MIP-SL process. A two-way linear motion approach has been developed for the quick spreading of liquid resin into uniform thin layers. The system design and related settings for achieving a fabrication speed of a few seconds per layer are presented. Additionally, the hardware, software, and material setups for fabricating three-dimensional (3D) digital models are presented. Experimental studies using the developed testbed have been performed to verify the effectiveness and efficiency of the presented fast MIP-SL process. The test results illustrate that the newly developed process can build a moderately sized part within minutes instead of hours that are typically required. [DOI: 10.1115/1.4007465]

Keywords: additive manufacturing, high-speed fabrication, mask image projection, stereolithography, fast recoating

1.1 Building Speed Limitation of the MIP-SL Process. In the MIP-SL process, the building time of each layer consists of spreading liquid resin into a uniform thin layer and curing the formed liquid layer into a solid layer. Compared to a laser beam that is used in the SLA process, the DMD used in the MIP-SLA process can dramatically decrease the curing time of a layer. Hence, the bottleneck for achieving a fast building speed is the spreading of liquid resin into uniform thin layers, which is the focus of the paper.

Research systems (e.g., Refs. [2–8]) and commercial systems (e.g., Refs. [9,10]) have been developed before based on the mask image projection approach. Most of the developed systems are based on the top-down projection as shown in Fig. 1. Suppose \(d_{LT} \) is the layer thickness. After a previous layer has been cured, the platform in such a system usually moves down a certain distance \(d \) and then up by \(d_d\) in order to spread liquid resin into a uniform thin layer. In addition to the \(Z \) movement, a recoating process is usually required to sweep through the platform such that the top surface can be flattened. For resin with low viscosity, a deep-dip recoating approach has also been developed to replace the surface sweeping approach. After the up and down movements in the \(Z \) axis, a sufficient waiting time is required for the liquid resin to settle down into a flat surface. However, such recoating methods typically take over a minute, which limits the building speed of the MIP-SL process. Consequently, the building time of such MIP-SL systems is still measured in hours.

1.2 Contributions. To address the building speed limitation of the MIP-SL process, we present a novel approach for quickly...
spreading liquid resin into uniform thin layers. Our approach is based on a two-way movement design in a bottom-up projection system. We addressed the related challenge of large attaching forces in the bottom-up projection system. By optimizing the process settings, we illustrate that the preparation of a uniform thin layer can be done within seconds. Consequently, the developed fast MIP-SL process can build moderate sized parts in minutes instead of hours.

2 Bottom-Up Projection Based MIP-SL System

In addition to the top-down projection approach as shown in Fig. 1, another projection approach used in the MIP-SL process is the bottom-up projection as shown in Fig. 2. That is, the mask image is projected onto the bottom of a transparent tank. After a layer is cured at the bottom of the built part, the platform is moved up and then down to form a small gap with the bottom surface of the resin tank. A uniform thin layer can be achieved after the formed gap is filled with liquid resin.

2.1 Advantages of the Bottom-Up Projection System. A bottom-up projection based system has several advantages over a top-down projection based system. (1) The container depth is independent of the part height. Thus, a shallow vat can be used to reduce the required volume of the liquid resin. During the building process liquid resin can be added by a pump when needed. (2) Recoating is achieved by constraining liquid resin between the previously cured layers and the resin tank. Hence, no additional sweeping is needed for flattening the resin surface. (3) Much smaller layer thickness can be achieved since the gap size is only determined by the Z stage resolution regardless of the fluid properties of liquid resin. (4) The curing of liquid resin is sealed from the oxygen-rich environment. By eliminating the oxygen inhibition effect, the liquid photopolymer resin can be cured faster.

2.2 Challenges of the Bottom-Up Projection System. Despite the advantages, the bottom-up projection based system has not been widely used in the SLA and MIP-SL processes. A main reason is that the separation of the cured part from the tank surface is difficult. That is, in the bottom-up projection based MIP-SL process, a cured layer is sandwiched between the previous layer and the resin vat. The solidified material may adhere strongly to the corresponding rigid or semiflexible transparent solidification substrate, causing the object to break or deform when the build platform moves up from the vat during the building process.

One approach to prevent the detachment of a cured layer from the built part is to increase its exposure such that the cured layer can strongly bond to the previous layers. However, such overcuring will also lead to poor surface quality and inaccurate dimensions. Another approach to address the problem is to apply a certain type of coating on the resin vat to reduce the attachment force of a cured layer. Suitable coatings, including Teflon and silicone films, can help the separation of the part from the vat [11,12]. A coated Teflon glass has also been used in the machine of Denken [13] and EnvisionTEC [9]. However, even with the intermediate material, the separation force can still be large. Huang and Jiang [12] investigated the attachment force for the coating of an elastic silicone film. Based on a developed on-line force monitoring system, test results indicate that the pulling force increases linearly with the size of the working area. Experiments indicate that, for a square of 60 × 60 mm, the pulling force to separate the part from the film is greater than 60 N. Such a large attachment force between the cured layer and the vat is a key challenge that needs to be addressed in the bottom-up projection based MIP-SL process.

To reduce the large attachment force, another approach developed by EnvisionTEC in its Perfactory Systems [9] is to incorporate additional mechanisms that add tilting motions in the part separation. That is, during the separation, one side of the platform can be moved up slowly before the other side. In this way, instead of the pulling-up, the part can be peeled off from the vat surface. Hence the detaching force would be significantly reduced. However, such additional tilting motion will also reduce the building speed of the MIP-SL process.

We address the large separation force and the related speed problem by developing a two-way movement method. For the purpose of easy sliding between the built part and the resin tank, we used another type of coating material, polydimethylsiloxane (PDMS, Sylgard 184, Dow Corning). The coating selection is based on the ability of PDMS in inhibiting free-radical polymerization near its surface, as shown by Dendukuri et al. [14]. In their research, it was identified that a very thin oxygen-aided inhibition layer (~2.5 μm) is formed that can prevent the cured layer from attaching to the PDMS film. Thus, curing the cured layers can easily slide on the PDMS film. Based on the approach, a fast MIP-SL process has been developed that can build a CAD model in minutes.

The remainder of the paper is organized as follows. Part separation study based on the PDMS film is presented in Sec. 3. A two-way movement approach to reduce the part separation force is presented in Sec. 4. The process settings and the related building time analysis are presented in Sec. 5. The experimental setup for performing physical experiments is discussed in Sec. 6. The experimental results of multiple test cases are presented in Sec. 7. Finally, conclusions with future work are given in Sec. 8.

3 Part Separation Study Based on PDMS

In order to separate the cured part from the PDMS film, a simple and intuitive approach is to directly move the platform up a
certain distance $d$ and then down by $d_d T$ where $d_d T$ is the layer thickness. Since one layer thickness is usually very small (50–200 μm), the distance $d$ is usually much larger in order for the resin to fully fill the gap (e.g., 5 mm). We studied the part separation force of a cured layer from a coated PDMS glass based on such movements. The PDMS film thickness is set at 1 mm. A set of physical experiments has been designed and performed to understand the separation force based on such an approach.

Figure 3 shows the setup for measuring the pulling-up force. Two FlexiForce sensors (Tekscan, South Boston, MA) with a range of 0–25 lbs are sandwiched between the fixture and the vat. The two sensors are connected to a microcontroller, which can sample and record the sensors’ readouts at over 3 KHz. Since the vat is free at the bottom and the side, and only fixed at the top, the pulling force by the part will be transferred to the sensors when the platform rises. In the experiments, we first use a given mask image to build a certain number of layers (e.g., 25 layers). The layer thickness is set at 0.2 mm. We then begin to record the separation force in the building process of the next few layers. For each layer, after the designed mask image has been exposed for a certain time, the platform is raised up slowly at 0.6 mm/s for 5 mm and the related readouts of the sensors are then recorded.

In our study, we considered three factors that may affect the separation force, including (1) exposure time, (2) image area, and (3) image shape. To understand the effects of these factors, designed experiments were conducted. Seven projection patterns were used for testing the effect of image shape. They are shown in Fig. 3, which include circle band, hexagon, t-shape, square, star-shape, triangle, and u-shape. For comparison, all the projection patterns have the same area in the tests. The separation forces of a cured layer were measured based on each of the seven projection patterns. Figure 4 shows the measured separation forces of a sensor for different test cases. The horizontal axis indicates the distance in the Z direction (in the unit of 10 μm) and the vertical axis indicates the measured pulling force (in ounces).

It can be observed from the experimental results that:

1. As the Z stage moves up, the separation force increases gradually. After the cured layer is detached from the PDMS film, the separation force will drop rapidly from the peak value to 0.
2. Due to the flexibility of the PDMS film, the pulling-up force is rather small within a moving distance that is less than 200 μm.
3. The peak force gets larger when the same mask image is exposed longer.
4. The peak force gets larger when a larger image area is projected.
5. The image shape has more complex effects on the peak force. In addition, their effects may interact with the exposure time and the projection area.
6. With the coated PDMS film on the vat, the separation force is still considerably large (~100 oz or 27.8 N for an image area of 625 mm² with 1 s exposure).

4 Two-Way Movement Design for the Fast MIP-SL Process

The experiment results indicate that the suction force between the cured layer and the PDMS film is large during the pulling-up process. Such a large force on the cured layer may cause the building process to fail if the bonding force between the current layer and previous layers is smaller than the suction force. In addition, after building multiple layers, such forces on the PDMS film may lead to cracks in the film due to material fatigue caused by the cyclic loading.

Based on the PDMS film, a two-channel design [15] was presented for the multimaterial MIP-SL process. However, such an approach, mainly designed for switching tanks, is not suitable for the fast building process. In the two-channel design, the building
of each layer requires a full cyclic motion, including both moving the platform up and down in the Z axis, and moving the tank back and forth in the X axis. Such motions will slow down the building process. To facilitate a high-speed MIP-SL process based on the bottom-up projection, we develop a novel two-way movement design that requires much less motions than the two-channel design. The developed approach is motivated by the following observations:

1. As shown in Fig. 4, the pulling-up force is negligible for the Z movement of a small distance (e.g., 50 or 100 μm) based on the 1 mm thick PDMS film.
2. The oxygen-aided inhibition around the PDMS surface leaves a nonpolymerized lubricating layer near the PDMS film. Therefore, the cured layer can easily slide on the PDMS surface.

The two-way movement design, as discussed in Sec. 4.1, can effectively address the large separation force that is problematic, while achieving a fast building speed at the same time.

4.1 Two-Way Movement Design. An illustration of the fast MIP-SL process based on the two-way movement design is shown in Fig. 5. In our method, a transparent PDMS film is first applied on the bottom surface of a transparent glass vat.

1. After a mask image is exposed to cure a layer, the platform is moved up in the Z axis for one layer thickness (e.g., 50 μm). Accordingly, the regions of the PDMS film related to the shape of the cured layer will be pulled up by the suction force. However, the force is small due to the super elasticity of the PDMS film. Note that there is no liquid resin between the cured layer and the PDMS film at this moment.
2. The tank is moved along the X axis for a certain distance Δx. A good property of the PDMS film is that a very thin oxygen-aided inhibition layer (∼2.5 μm) is formed near the PDMS film that can provide a nonpolymerized lubricating layer for easy sliding [14]. If the moving distance is sufficiently large (e.g., larger than the extent size of the cured layer in the X axis), the elastic deformation of the pulled-up PDMS film will be released by such a sliding movement. Hence, at the end of the X movement, liquid resin will be filled in the small gap between the cured layer and the PDMS film.
3. The mask image of a new layer can now be projected at the bottom surface to cure the next layer. These three steps can then be repeated by moving the tank in an opposite direction. Note that, to achieve the motion in the X direction, we only move the tank and the related frame. There is no relative motion between the platform and the projection device. Hence the XY accuracy of the MIP-SL system will not be affected by the X translations.

4.2 Separation Force Study Based on the Two-Way Movement Design. To verify the proposed two-way movement design, a set of experiments was conducted based on the setup as shown in Fig. 3. The same set of mask patterns was used in building test layers. The same exposure time and layer thickness were used (1 s and 0.2 mm, respectively). The building process as shown in Fig. 5 was first used in building a set of layers. In the experiments, the tank was translated in the X axis by 20 mm. The moving speed is set at 25 mm/s. After the layers have been built, the pulling-up forces in the Z axis during building the next layer were recorded. However, instead of curing a new layer as shown in step 3, the part is moved up slowly at 0.6 mm/s for 2.5 mm. The measured forces of a sensor in the Z axis during the aforementioned three steps are shown in Fig. 6. In each figure, the curves record the test results based on a sampling resolution of 80 ms.

The figures show that the force in the Z direction is rather small when the platform is moved up by 0.2 mm. During the remaining two steps (i.e., sliding on the PDMS film and the platform pulling-up), the peak separation forces are also relatively small (around 2–6 oz or 0.56–1.67 N). Such measured forces are only 3–4% of the related ones as shown in Fig. 4. Hence the two-way movement design can effectively reduce the large separation force in the bottom-up projection system.

4.3 Shearing Force Study in the X Axis. In the two-way movement design, cured layers can easily slide on the PDMS surface. The FlexiForce sensors were used in a modified setup to measure the shearing force in the X direction. However, no meaningful readouts were recorded from the sensors. To quantitatively estimate the value of the shearing force in the X axis, a set of square rods with different sizes was built using the two-way movement design. The built rods shown in Fig. 7 are 10 mm tall. The minimum cross section size is 0.4 × 0.4 mm. Note that we also successfully built rods with even smaller sizes. However, the rods were so fragile that they lost the mechanical strength to...
sustain themselves when the part was taken out of the resin vat and washed in isopropyl alcohol. Nevertheless, for a rod with a size of $0.4 \times 0.4$ mm, the maximum tangential force that can be added on it can be analytically estimated. As shown in Fig. 7, the testing rods in the experiment can be modeled as a cantilever beam. Suppose the length of the beam is $L$, the size of the beam section is $b \times b$, the force in tangent direction is $F$. The maximum bending stress at the end can be calculated as $\sigma = Mc/I$, where $I$ is the section modulus, $I = b^4/12$, and $c = b/2$. Substituting these values for their variables, the resultant equation is $\sigma = 6FL/b^3$. Suppose the allowable blending stress is $[\sigma]$ and the minimal beam section size is $[b]$, we will have the following equation: $F \leq [\sigma][b]^3/6L$. The material used in our tests has the following parameters: $[\sigma] = 65$ MPa, $[b] = 0.4$ mm, and $L = 10$ mm. According to the equation, the upper bound of the tangential force is only 0.07 N or 0.25 oz. Compared with the separation force in the $Z$ direction, the shearing force in the $X$ direction is rather small.

5 A Fast MIP-SL Process and Its Building Speed Analysis

The two-way movement design enables the quick spreading of liquid resin into a uniform thin layer. In addition, the DMD-based digital mask projection enables the fast curing of the spread liquid resin into a desired solid layer. Consequently, for a given 3D CAD model, a fast MIP-SL process can fabricate a physical object within a short building time. The curing characteristics and the two-way movement settings of the developed MIP-SL process are presented as follows. A detailed analysis of its building time is also discussed.

5.1 Curing Characteristics. There are two types of photopolymer systems, acrylate chemistry and cationic photopolymerization, in the SLA process [16]. Acrylate chemistry polymerizes via a free-radical mechanism, while cationic photopolymerization undergoes ring-opening reactions in the presence of cationic photoinitiators. The monomer propagation for cationic reactions requires relatively higher activation energy. Consequently, the photospeed of acrylate-based photopolymers is higher due to the lower activation energy for free-radical reactions. Considering the photospeed difference, we selected the photopolymer resins based on acrylate chemistry for the developed fast MIP-SL process. As shown in Sec. 6, our projection system can cure a layer within a short exposure time (<500 ms). Such a fast curing time contributes to the desired fast MIP-SL process for building 3D objects in minutes.

After an image is exposed for a certain time ($T_{\text{projection}}$), a waiting time, $T_{\text{wait}}$, is required before the layer can be moved up for one layer thickness (i.e., step 1 in Fig. 5). Such a waiting time is critical in order for the acrylate resin to complete the solidification process and gain sufficient strength for the $Z$ movement. Otherwise, the building process may fail. The waiting time is dependent on the resin’s curing property. Due to the fast photospeed of the acrylate resins, the waiting time in our system is short (~300 ms in our tests).
5.2 Two-Way Movement Settings. In the two-way movement design, the cured part is first moved up for one layer in the $Z$ axis and the tank is then translated in the $X$ axis for a certain distance. The two linear movements have different accuracy and speed requirements.

(1) The $Z$ movement needs to be accurate since it will determine the layer thickness of the next layer. The $Z$ stage also needs to have a resolution that is much smaller than a layer thickness. Accordingly, to ensure the desired accuracy and resolution, we set small acceleration and velocity values in the $Z$ movement. The slow movement of the cured part also enables the PDMS film to fully elastically deform for a small attaching force. However, the movement time in the $Z$ axis ($T_Z$) is still reasonably short ($\sim$0.4 s in our tests) since only a small moving distance is required (e.g., 50 or 100 μm).

(2) The tank needs to be moved in the $X$ axis for a certain distance to release the elastic deformation of the PDMS film. The $X$ moving distance is related to the shape and size of the cured layer and less than the extent size of the cured layer in the $X$ axis. Since the relative position of the platform and the projection system will not change during the $X$ movement, the accuracy and resolution requirements on the $X$ movement are not as high as those on the $Z$ movement. Hence a much larger acceleration and velocity can be applied in the $X$ movement to reduce the movement time in the $X$ axis ($T_X$).

In our testbed, we used a $Z$ linear stage with a thread of 0.5 mm/round and a $X$ linear stage with a thread of 25.4 mm/round. The moving time for different displacement distances in our prototyping system was calibrated for both linear stages. The results are plotted as diamond-shape and square-shape lines in Fig. 8 for the $Z$ and $X$ stages, respectively. As shown in the figure, the movement in the $Z$ axis is much slower than that in the $X$ axis. The movement time required to complete a moving distance in the $Z$ axis can be identified based on the calibration data.

After the $X$ movement, another waiting time, $T_{wait_X}$, is required in order for the flowing liquid resin to settle. Otherwise, the building process may fail. The waiting time caused by the $X$ motions is related to the movement distance and the moving speed. Due to the small gap between the cured part and the PDMS film, the required waiting time is typically short ($\sim$100 ms). After the waiting time of $T_{wait_X}$, the liquid resin forms a uniform thin layer, which is ready for the next layer to be built. The process can then be repeated after the related mask image is exposed.

5.3 The Building Time of a Layer. As shown in Fig. 9, the building time of each layer is thus the sum of all the aforementioned steps

$$T_{Layer} = T_{Projection} + T_{wait_Projection} + T_Z + T_X + T_{Wait_X}$$

The first two items, $T_{Projection}$ and $T_{wait_Projection}$, are related to the curing characteristics of the photopolymer resins used in the MIP-SL process. The photopolymer resins based on acrylate chemistry can be quickly cured. A stronger light source used in the projection system can further reduce the projection time $T_{Projection}$.

The other three items, $T_Z$, $T_X$, and $T_{Wait_X}$, are related to the two-way movement design. $T_Z$ is related to the layer thickness and
the moving velocity in the Z axis. $T_X$ is related to the size of the cured layer and the moving velocity in the X axis. A linear stage with a higher speed can be used to further reduce the movement time $T_X$. $T_{\text{wait, } X}$ is determined by the gap distance between the PDMS and the cured layer, the moving velocity of the tank, the shape of the cured layer, and the flow properties of the liquid resin. For a typical layer thickness that is usually small, $T_{\text{wait, } X}$ is reasonably short (~100 ms in our tests).

Note that the projection time $T_{\text{projection}}$ for the first few layers is much longer (e.g., 3–4 s) to ensure the initial layers can be strongly bonded to the build platform. For all the other layers, the total building time of a layer is usually short (a few seconds in our tests). Hence, a fast fabrication speed can be achieved in the developed process (e.g., building 3 mm height per minute).

6 Experimental Setup

6.1 Hardware System. A prototype system has been built to verify the developed process. The hardware setup of the fast MIP-SL system is shown in Fig. 10. In the designed system, an off-the-shelf projector (CASIO XJ-S36) was used. 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 48 × 36 mm. Two different layer thicknesses commonly used in the MIP-SL process were tested. A 50 μm layer thickness was used in the fabrication of a gear model. The mask image projection time was 0.35 s for each layer except the base. The projection waiting time was set at 0.1 s. For all the other models, a 100 μm layer thickness was used in their building processes. Due to the larger layer thickness, the exposure times for S1500 based on our projection system are set at 0.3 s and 0.45 s, respectively. The exposure times for Acryl R5 are set at 0.4 s and 0.55 s for curing depths of 0.05 mm and 0.1 mm, respectively.

7 Experimental Results and Discussion

Tests have been performed to verify the building speed of the developed prototyping system. The results of the designed tests have demonstrated that the presented MIP-SL process can build 3D models in minutes instead of hours.

7.1 Test Procedures and Results. A set of CAD models with different complexity was used in our tests. The screenshots of six input CAD models are shown in Figs. 12(a)–17(a). The related STL files have triangle numbers ranging from several hundreds to 1.2 million (refer to Table 1). The materials of the prototypes were Perforamy™ S1500 (yellow) and Acryl R5 (red) from EnvisionTEC Inc. (Ferndale, MI), were used in testing the developed fast MIP-SL process. Both resins belong to acrylate. For curing depths of 0.05 mm and 0.1 mm, the exposure times for S1500 based on our projection system are set at 0.3 s and 0.45 s, respectively. The exposure times for Acryl R5 are set at 0.4 s and 0.55 s for curing depths of 0.05 mm and 0.1 mm, respectively.

Table 1 Building time statistics

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<td>$T_{\text{wait, projection}}$ (s)</td>
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aThe projection and waiting time for R5 resin; others are for S1500.
bDifferent X moving distances were used in building the bottom (1st layer–19th layer) and the top (20th layer–83rd layer) portions of the brush.
thickness, a longer image exposure and projection waiting times were used (0.45 and 0.3 s, respectively, in the tests). Accordingly, the Z movement will also take a longer time for a larger layer thickness. In the tests, the movement time in the Z axis ($T_Z$) is 0.32 and 0.42 s for the layer thickness of 50 µm and 100 µm, respectively.

The required moving distance in the X axis is related to the size and shape of the cured layer. For a layer with a big cross-sectional area (e.g., the models of a head and a statue), the X translation distance is set to a value that is close to the X extent size. Due to the large movement, the X waiting time was also set longer. In comparison, for a layer with a small cross-sectional area (e.g., the models of a hearing aid shell and the top portion of a brush), the X translation distance can be much smaller than the extent size of the layer in the X axis. However, due to the fast moving speed in the X axis, the differences on $T_X$ are usually small (less than 1 s as shown in Table 1).

Two types of resins, SI500 and Acryl R5, were tested. Their curing characteristics are slightly different. For the same layer thickness, the curing of Acryl R5 takes ~0.1 s longer than that of SI500. The viscosities of the two resins are also slightly different. However, the same settings can be used in the two-way movement design based on the two resins.

Figures 12–17 show the built objects based on the developed fast MIP-SL process. The quality of the built objects was examined to be satisfactory. Both surface finish and dimension were analyzed to be acceptable. In our prototyping system, the nominal size of a pixel is 47 µm. The fine image resolution enables the mesoscale features (i.e., in the range of 0.1–1 mm) to be well captured in the built physical objects, e.g., the lip of the human head, the cloth folds in the Beethoven statue, and the dentures in the teeth model.

### 7.2 Building Time Analysis

All the models shown in Figs. 12–17 were built within 12 min using our prototyping system. The models with less than 100 layers (e.g., the gear, the teeth, and the brush) only require 2–3 min to be built. A statistic of the building time is given in Table 1.

A much larger exposure time (e.g., 4–5 s) was required for the first few layers in order to build a base. Consequently, the built objects and the build platform can be well bonded. For all other layers, as shown in Fig. 18, the building time of a layer ($T_{Layer}$) in our MIP-SL process is only 1.4–2.5 s. The variation on $T_{Layer}$ is mainly due to different layer thicknesses and the X moving distances. For an average of 2 s per layer and a layer thickness of 0.1 mm, the building speed of the developed MIP-SL process is ~3 mm per minute, or 180 mm per hour. To the best of our knowledge, such a MIP-SL process is one of the fastest layer-based...
additive manufacturing processes that have been developed. A video of building the gear model as shown in Fig. 12(a) can be found in Ref. [17].

8 Conclusions

A novel mask-image-projection-based stereolithography process has been presented for fabricating 3D objects with fast building speed. The proposed approach is based on projecting mask images bottom-up on a PDMS coated glass substrate. A new two-way movement design has been presented for quickly spreading liquid resin into uniform thin layers. Such a design can significantly reduce the separation force between cured layers and the resin tank. Experimental results verified that the separation force as well as the sliding force is relatively small during the two-way movement process. The motions related to the two-way movement design can also be performed quickly. The MIP-SL process developed based on such a recoating approach can successfully fabricate 3D objects with satisfactory quality in a short time (usually in minutes).

Some future work to further improve the building speed of the developed MIP-SL process includes (1) investigating the settings of $T_x$ and $T_{\text{wait},x}$ based on given layers for the best performance; (2) testing faster moving speeds in the X and Z axes; and (3) testing the two-way movement design in prototyping systems with larger XY extent sizes.

References


Fig. 18 Layer building time of the test cases