Technical Development of Multi-Resin Three-Dimensional Printer Using Bottom-Up Method

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Abstract: The use of multi-resins entails certain challenges due to inter-stain in the intermediate layer of cured resins and misalignment caused by the use of multi-light sources or vat switching. This study proposes a new mechanism for a multi-resin three-dimensional printer that can fabricate physical models consisting of different resins without misalignment using the bottom-up method with a digital projector and a clean modulus that can avoid inter-staining. Experimental results show that the proposed C-arm design offers self-alignment when the platform is switched or during cleaning. The proposed clean modulus can also prevent inter-staining, thus producing a clear boundary layer. The linear and angular dimensions are respectively accurate within 20 μm and 0.2°.

Keywords: Multi-resin; Inter-stain; Three-dimensional printer

Introduction

Most additive manufacturing (AM) systems are designed to fabricate parts using a single material, and cannot use multiple materials to construct products. One aspect of AM development is the use of multi-material additive manufacturing (MMAM) technologies to produce parts using different materials [1-3]. Table 1 lists MMAM technologies and their associated methods. Fused deposition modeling (FDM) is a system that allows for the construction of multi-material prototypes but the diameters of the filament and extrudate produce an unacceptably low accuracy of only about 80 μm [4-5]. An ink-jet printing method that uses a photo-curable resin, such as the OBJET system, can also be used to construct products using different materials for a single part, but the printer can frequently become clogged with resin, and replacement cartridges are expensive. Using multiple resins for top-down SL allows for the direct construction of multi-resin objects but the residual resin on the model surface must be cleaned when the vats are switched, thus limiting practical applications. The cost of the resin

used for twin-vat SL is almost twice that for single-vat SL, so bottom-up SL provides significant financial savings.

Few studies have considered recent developments in MMAM [6-9]. Zhou proposed a multi-material mask-image-projection-SL (MIP-SL) system that uses the bottom-up method [8]. This system consists of two vats for two different resins, along with two brush tanks that remove the majority of the liquid resin on the bottom and on the perimeter of the part, an ultrasonic cleaner for final cleaning of the residual resin and a fan to dry solvents such as methanol. These systems use a platform that is rotated by a motor to switch functions. A projector is fixed beneath the platform and projects the sliced layer pattern. The cleaner prevents inter-staining on the boundary layer when residual resin penetrates the cured portion next to the portion that is curing. The main disadvantage of this design is that the platform needs rotate very slowly because all of the devices are heavy. Although the bottom-up SL allows for the construction of objects using multiple resins, the mechanical design must allow for increased fabrication speed.

This study proposes a mechanism and a clean

module to prevent misalignment and inter-staining. The developed multi-resin three-dimensional printer (3DP) adopts a bottom-up method. The system consists of a digital light projector (DLP), a C-arm module, two vats and an air-bubble clean module. A two-dimensional calibration benchmark is used to calibrate the actual size and angle, and thus determine system accuracy. A twin-resin model is constructed to demonstrate that two resins can be used for fabrication and to verify the construction speed and the absence of inter-staining on the boundary layer. The bonding interface between two resins is observed using an optical microscope and the merits of the proposed system are discussed.

Multi-material additive manufacturing (MMAM) technologies used to produce complex structures with multiple functions in a single part include FDM, SL or ink-jet printing methods [4-5, 9]. The advantages and disadvantages of each method are listed in Table 1. FDM uses a thermally sensitive material to construct a complex structure with multiple colors in a single object using multiple heating nozzles. However, this system has a low accuracy and a slow processing speed. However, it produces less toxic residual material so it commonly used in bioprinting to produce scaffolds [10]. The ink-jet printing method uses jetting technology, so more than 50 materials can be used to construct objects with multiple requirements in a single part. The liquid-state photo-curable material is jetted in individual drops using a piezoelectric nozzle and solidified using cooling or a chemical reaction. The main disadvantages of this process are higher equipment costs and a greater failure rate due to clogging of the piezoelectric nozzles. However, the jetting method's accuracy is within 40 μm , making it more accurate than other methods. Objects that feature multiple materials in a single part can also be produced by the system using SL, which outperforms FDM in terms of process time and the accuracy, and offers performance similar to that of ink-jet printing. The lower equipment cost for SL is the most important benefit. Multiple material processes that use SL method can be divided into two types, depending on the projection type: top-down and bottom-up. Studies of multi-material SL systems mostly use top-down projection. However, a large vat is required to maintain the level of the photo-curable resin when projecting the pattern from top to bottom, which can increase material waste and difficulty in cleaning.

Materials and Methods

Development of multi-resin 3DP

This study fabricates a highly accurate prototype

constructed using two different resins. Figure 1(A) shows a multi-resin 3DP that uses a bottom-up method. The system consists of two vats for the different resins, a clean vat for the solvent with two air nozzle arrays, a

C-arm mechanism for the platform and projector (also called a light engine) and an air compressor that produces bubbles in the clean vat.

The forming procedure has three stages: the sacrificial layer, the manufacturing process and the post process. To form the sacrificial layer, a thickness of raft layer or a support structure of about 1 mm is constructed to increase the bonding force between the platform and the object to be constructed. The digital model is then sliced into different parts, according to the type of resin that is to be used layer by layer, and then imported to

Table 1. Advantages and disadvantages of multi-material additive manufacturing technologies.

Method	FDM ^a	SL ^b	Ink-jet printing	DLP ^c
Energy Source	Thermal	Laser / UV	UV	Visible light/UV
Accuracy (μm)	127-330	50	29	15-150
Max. Build-space (mm)	914*610*914	1500*750*550	508*381*229	192*120*230
Print speed (mm / hr)	N/A	N/A	5-15	22
Material	TP	PP	PP	PP
Cost (USD)	<3,000	N/A	<180,000	<12,000
Advantages	Desktop scale; consistent throughput	Good accuracy	Good printing speed; good accuracy	High printing speed; High accuracy
Limitations	Slower; reduced strength in the vertical direction	Limited to curable materials; slow	High cost; requires post-processing	Limited to curable materials; small build space

^a: Fused Deposition modeling.

^b: Stereolithography.

^c: Direct Light Projection.

TP: Thermoplastic.

PP: Photopolymers.

the proposed multi-resin 3DP to fabricate the physical

object. This study uses only two vats to demonstrate increased fabrication speed. One cleaning vat is used to demonstrate absence of inter-staining when two resins are used.

Three major modules are used for the multi-resin 3D printer: a DLP light engine, a coaxial rotating platform and a clean modulus. The light engine emits UV light with a wavelength of 405 nm. Therefore, a photo-initiator that reacts to UV light is added to the resin. Two different color pigments are separately added to the resin. The photo-curable resin consists of trimethylolpropane triacrylate (TMPTA, Double Bond Chemical Co.) as the base monomer resin, and trimethylbenzoyl diphenylphosphine oxide (TPO, Double Bond Chemical Co.) as the UV light photo-initiator and two pigments (blue and yellow, Double Bond Chemical Co.). Table 2 lists the composition of the resins. The light engine emits UV light and induces cross-linking in the photo-curable resin to form the solid phase from the liquid state.

Figure 1. (A) Illustration of the multi-vat 3D printer; (B) mechanism for the C-arm module; (C) illustration of a clean module; (D) assembled multi-vat 3D printer.

Table 2. Composition of photo-curable resin.

Item name	Weight %	Role
TMPTA	99.4	Base monomer
TPO	0.5	Photo-initiator
Pigment	0.1	Dye

Figure 1 (b) shows the mechanical design of the coaxial C-arm rotating platform. The key components of this system are a light engine, a rotary Z-axis and the platform. A C-arm fixes the platform and the light engine and aligns them so that the layer pattern can be projected. There is no misalignment when the platform moves repeatedly.

The clean module is used to remove the residual resin from the surface of the constructed object before the platform moves to another vat. Figure 1 (c) shows the solvent in the clean vat and one pair of air nozzle arrays generates a bubble to wash out the residual resin. In this study, the solvent is methanol, which is recycled. The solvent is cleaned by passing through a filter membrane that collects the suspended pigments in the solvent. The platform moves to the cleaning module and immerses the constructed object in a clean vat before it switches to another resin vat. The air bubble is generated by an air nozzle array in the solvent and removes the un-cured resin in 10 seconds.

The extraction method is key to the success of a bottom-up 3D printer because the currently curing layer bonds to the previously cured layer and the bottom surface of the vat. Many studies use different extraction methods to eliminate the extraction force by sliding or rotating the cured object. Few studies modify the properties of the intermediate layer [8]. A thin elastic film, such as silicon rubber or PDMS, (Polydimethylsiloxane) is frequently coated onto the bottom surface of the vat as an intermediate layer to reduce the extraction force. The cheapest and simplest method is to use a Teflon film but its lifetime is shorter than that of PDMS. In this study, a polydimethylsiloxane (PDMS, Sil-More Industrial Ltd.) thin film is coated onto the bottom surface of the vat, which is elastic, and allows high light transmittance and makes a deformable interface that allows for a smaller extraction force when the platform is lifted. Both vats are coated with PDMS with a thickness of 1mm.

Benchmarks

Dimensional calibration is essential for high accuracy. In this study, a benchmark model with a circle and various angles is used, as shown in Figs. 2 (a) and (b). The dimensions are 40×40 mm and the thickness is 5 mm. The constructed model is then measured using a non-contact video measurement system (EM-2.5D,

MIMN TAIY Co., LTD) and the error is determined by comparing the dimensions in a CAD model and the measurement data.

Figure 2. Benchmark for dimensional calibration of (a) three-dimensional model and (b) symbols for each angle and dimension.

Resin inter-stain effect in the boundary layer

The cleaning method must prevent resin inter-staining at the boundary layer when two different resins are used to build the object. Two observable models are used to verify the absence of resin inter-staining in any direction for the constructed object. Figure 3 (a) shows a Tai-Chi model that has two resins in one layer (x-y plane). Figure 3 (b) shows a Sunray model that uses two resins in the Z-axis direction.

Figure 3. Benchmark for observing inter-staining effect of (a) a Tai-Chi model and (b) a Sunray model.

Results

Figure 1 (d) shows the assembled multi-resin SL

system. There are two resin vats and one clean vat in the working area. One rotary stage in the C-arm structure supports the DLP light engine and the platform. The resolution of the DLP light engine is 720P (VGA 1280*800) and the focal distance ranges from 10 to 15 mm. One small motor is connected to a thin black plate above the emission window of the light engine that acts as a shutter controller.

Figure 4 shows the benchmark object for dimensional calibration. The layer thickness and the exposure time are respectively 20 μm and 5 seconds. Five objects are constructed and their features are measured ($n=5$). The dimensions and the angles for these five objects are listed in Table 3. A comparison of the fabricated object with the original model shows that the maximum and minimum angular errors are respectively 0.6 degrees (A10) and 0.1 degrees (A1, A4 and A6). The respective errors in the length and width are 10 μm and 20 μm .

Figure 4. Fabricated object for dimensional calibration.

Table 3. Result for the two-dimensional model at various angles.

Symbol	CAD model	Physical object	Error
A1	15°	14.8°	-0.2°
A2	65°	99.8°	-0.2°
A3	100°	64.8°	-0.2°
A4	25°	24.8°	-0.2°
A5	60°	60.0°	0°
A6	30°	30.2°	+0.2°
A7	45°	45.1°	+0.1°
A8	45°	44.9°	-0.1°
A9	90°	90.2°	+0.2°
A10	75°	75.2°	+0.2°
L	40 mm	40.0 mm	+0 mm
W	40 mm	39.98 mm	-0.02 mm
T	5 mm	5.01 mm	+0.01 mm

L: length.

W: width.

T: thickness

One of difficulties for multi-resin object fabrication is the delamination problem due to different shrinkage ratios. Previous studies have shown that blending micro-size filler with the resin reduces the shrinkage ratio, but this increases the compressive strength of the solidified part [11]. In this study, the shrinkage ratio for this resin is $0.48 \mu\text{m}/\text{cm}$. Figure 5 (a) shows the result of the Tai-Chi model. The images on the right and left respectively show the two masking patterns that are required to form one layer and the boundary of the two cured portions is strongly bonded. No delamination occurs after post-processing because the resin in the two vats is the same but the pigment colors are different.

Figure 5. Fabricated Tai-Chi object to observe the delamination of two-resin bonding at the boundary layer.

Figure 6 shows the fabricated Sunray model. The layer thickness and the exposure time are respectively $20 \mu\text{m}$ and 5 seconds. The lower left image shows the constructed object with a sacrificial layer after removal from the platform. The sacrificial layer was removed and cut in half to observe the cross-sectional profile, as shown in upper left image. The boundary layer was observed using an optical microscope and the image is shown on the right. It is seen that there is no resin inter-staining, so the proposed clean module completely washes the residual resin from the constructed object before the platform switches to a different vat.

Figure 6. Fabricated Sunray object for observing the inter-staining effect at the boundary layer.

Discussion

Accuracy calibration

Factors that reduce the accuracy of the SL method are the resolution of the light engine, distortion of the layer pattern projection and the shrinkage ratio of the resin. In this study, the light engine is a DLP projector. The resolution depends on the number of pixels in the DMD chip. The resolution of 720P is 1280×800 for the DMD chip, allowing an accuracy of $56 \mu\text{m}$ in the direction of the length (x-axis) and width (y-axis). The accuracy in the direction of the height (z-axis) is $20 \mu\text{m}$ and depends on the ball screw used. Layer image distortion is common when the mask is projected onto the surface of the liquid resin because of incorrect hardware settings or optical aberrations in the lens. These distortions are classified as either barrel distortion, pincushion distortion or mustache distortion. One study used a projector-camera to estimate the image in the projector image plane and adjust the distorted image [12]. Most of the distortion was detected and calibrated using off-the-shelf components. Therefore, a calibration model that comprises a camera, a DLP light engine and a calibration image was used in this study to increase accuracy. After calibration, the two-dimensional benchmark with various angles was reproduced and measured. Table 3 lists the calibration results. The deviation in each angle is 0.2 degrees, and zero in some cases. The accuracy in the length and width is $20 \mu\text{m}$.

Merits of the developed multi-resin 3DP

In this study, the multi-resin 3DP uses mask-less projection with the bottom-up method to address these disadvantages. The optical microscope images show that combining air pressure and methanol solvent to clean prevents the contamination of the material when changing materials during the process. Furthermore, the advantage of this C-arm design is that the parallelism between specimen platform and project light image plane is easy to control because it is made by CNC cutting on one workpiece. To compare with the two-resin type of DLP 3D printing, this developed system can make a clear intermediate boundary on one layer with two-resin bonding.

Conclusion

This study proposes bottom-up multi-resin stereolithography using digital light projection. The proposed C-arm mechanism aligns the layer image and the platform during the fabrication process. No inter-staining occurs in the direction of construction or

the layer plane, so this clean method is very efficient. The dimensional and angular errors are respectively less than 0.2 mm and 0.2 degrees.

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