UV-CURABLE PDMS FOR ADDITIVE MANUFACTURING OF MICROFLUIDIC DEVICES

A THESIS

Presented to the University Honors Program

California State University, Long Beach

In Partial Fulfillment

of the Requirements for the

University Honors Program Certificate

Adam Grosvirt-Dramen

May 2018
I, THE UNDERSIGNED MEMBER OF THE COMMITTEE,

HAVE APPROVED THIS THESIS

UV-CURABLE PDMS FOR ADDITIVE MANUFACTURING OF MICROFLUIDIC DEVICES

By

Adam Grosvirt-Dramen

Roger C. Lo, Ph.D. (Thesis Advisor)  Chemical Engineering

California State University, Long Beach

May 2018
ABSTRACT

UV-CURABLE PDMS FOR ADDITIVE MANUFACTURING OF MICROFLUIDIC DEVICES

By

Adam Grosvirt-Dramen

May 2018

Microfluidics involves the study of fluid behaviors, controlled fluid manipulations, and the design of systems that can reliably perform such tasks at the microscale (typically tens to hundreds of micrometers). For over two decades, microfluidics has found applications as an enabling platform to miniaturize chemical and biological processes in various areas, such as biology, chemistry, engineering, and medicine. Poly(dimethylsiloxane), PDMS, is a common material of choice for microfluidic devices due to its elasticity, high optical transparency and biocompatibility. Soft lithography is a common technique to fabricate PDMS microfluidic devices, but it requires master preparation followed by casting and curing in a cleanroom. Non-cleanroom-based techniques have been demonstrated but they are still based on a molding process.

In this work, we seek to streamline the fabrication process by eliminating the molding step via formulating a UV-curable PDMS tailored for direct additive manufacturing. Advantages of this new approach facilitate rapid prototyping and significantly accelerate the development of microfluidic devices for desired applications.
ACKNOWLEDGEMENTS

I sincerely thank Dr. Roger C. Lo for his guidance, mentorship, and encouragement throughout my research career as my advisor. I am grateful that he took me into his lab to join his research projects. I am also grateful for the use of his laboratory equipment in the Department of Chemical Engineering.

Dr. Ehsan Barjasteh for his knowledge, guidance, and the laboratory equipment in the Department of Chemical Engineering and Department of Mechanical and Aerospace Engineering.

I would like to thank all of my friends from both Dr. Lo’s and Dr. Barjasteh’s labs that helped in this phase of my research.

I would like to thank those in the California State University, Long Beach Building Infrastructure Leading to Diversity (CSULB BUILD) Program, the Engineering Honors Program, and the University of Honors Program for the opportunity to pursue research.

This research was supported by the National Institute of General Medical Sciences of the National Institutes of Health under Award Numbers; 8UL1GM118979-02; 8TL4GM118980-02; 8RL5GM118978-02. The content is solely the responsibility of the authors and does not necessarily represent the official views of the National Institutes of Health.
TABLE OF CONTENTS

ABSTRACT ................................................................................................................................. i

LIST OF TABLES ....................................................................................................................... iv

LIST OF FIGURES ..................................................................................................................... v

1. INTRODUCTION .................................................................................................................. 1

2. MATERIALS AND METHODS ........................................................................................... 4

3. RESULTS AND DISCUSSION ............................................................................................ 10

4. CONCLUSION AND FUTURE WORK ................................................................................. 16

REFERENCES ............................................................................................................................ 20
## LIST OF TABLES

1. Cure Time Changes in Response to Curing Scale Reading ........................................ 8
2. Average Layer Thickness of PDMS Samples After Thermal Curing .......................... 10
3. Cure Depth for Each Concentration of TPO ........................................................ 12
4. Layer Cure Times for Each Concentration of TPO ............................................. 14
# LIST OF FIGURES

1. Microfabrication process for PDMS devices ................................................................. 1
2. 3D-printed tools ............................................................................................................... 5
3. Printed stencil sheets in a 3X5 array ............................................................................... 6
4. 3D-print test from Genomer 1231 ................................................................................. 7
5. UV intensity versus distance from source for different UV-LED types ....................... 12
6. Plot of the cure depth versus TPO concentration ......................................................... 13
7. Plot of layer cure time with varying TPO concentration ............................................... 14
CHAPTER 1

INTRODUCTION

Microfluidics is the study of fluid behaviors and their manipulations at the micrometer scale with specifically designed devices to perform such tasks. For over two decades, microfluidic technologies, also known as Lab-on-a-Chip, have found applications as an enabling platform for miniaturizing chemical and biological processes in various areas, such as medical diagnostics (1), drug screening (2), chemical synthesis (3), and more. The most popular material used to fabricate these devices is the polymer, polydimethylsiloxane (PDMS). The benefits of using PDMS in microfluidics include its high optical transparency, flexibility, and biocompatibility (4).

Traditionally, fabricating PDMS microfluidic devices involves both photolithography and soft lithography (Figure 1) (5,6). Photolithography is the process of preparing the master mold, and soft lithography is the process of casting and curing the device itself in a cleanroom. Although non-cleanroom-based techniques have been demonstrated, microfluidic devices still require a molding process (7).

Figure 1. Microfabrication process for PDMS devices. (a) Master mold preparation with a silicon wafer. Coat with a photoresist, SU-8, and cure with a mask of desired design. (b) PDMS fabrication using the master mold. Pour PDMS over the mold and leave in an oven to cure. Reproduced from (5).
Overall, the complete fabrication process is cost-, time-, and skill-intensive with the resulting devices being of variable qualities. A simpler, standardized fabrication process for microfluidic devices is needed, and the advent of 3D-printing technologies can satisfy this need. There are multiple kinds of 3D-printing techniques (8), but in this thesis we will only focus on two. Fused deposition modelling (FDM) is the first 3D-printing technique and involves extruding the build material layer-by-layer onto a build platform. Stereolithography is the second 3D-printing technique and involves photopolymerization to cure the 3D-model layer-by-layer from a reservoir of monomers. With direct 3D-printing, fabrication is cheaper, faster, and easier with higher reproducibility than traditional methods (9). The simpler fabrication process is preferable because no special training is required (10). However, available 3D-printing materials for microfluidic devices are limited and contrast greatly with the more popular PDMS.

Unfortunately, most 3D-printing technologies require thermoplastic polymers, which soften with the addition of heat. PDMS is a thermoset polymer, so it hardens, or cures, with the addition of heat and a curing agent. To bypass this obstacle, ultraviolet (UV) light can be used to cure the PDMS as it is being deposited on the printer’s build platform. This project aims to validate a method for developing and customizing UV-curable polymers for 3D-printing and in turn apply this method to 3D-print microfluidic devices with PDMS.

This study compares PDMS to another UV-curable polymer for direct 3D-printing of microfluidic devices. One benefit of the PDMS method is that it streamlines the fabrication process by avoiding the cost-, time-, and skill-intensive molding processes, which are common to fabricating microfluidic devices by other methods. The advantage of this streamlining is rapid prototyping and accelerating the design-to-device production cycle. Another benefit could be the ability for other researchers with specialty polymers to quickly determine the best method for
3D-printing with their polymer using a mass assay rather than individual testing. To test this potential benefit, we compare PDMS, a silicone-based material, to an acrylic resin; we will determine for the best 3D-printing formulation using two different methods. We compare the photocatalyst concentration, cure time, cure depth (11), and structure of both polymers. The ultimate goal of the project is to design a benchtop microfabrication process that can be used in any research or industry setting. The system will be simple and open-source, so those not familiar with microfabrication protocols could use this system for their research projects. All developments in this study will be shared under the Open Source Creative Commons License to aid research scientists globally.
CHAPTER 2

MATERIALS AND METHODS

Chemicals and equipment

The polymer to be used in this experiment is polydimethylsiloxane (PDMS) with its respective curing agent (Dow Corning Corps., Michigan, USA). Multiple photoinitiators are also used throughout this experiment: benzophenone, Irgacure 651, thioxathen, Irgacure 2100, and 2-hydroxy-2-methylpropriophenone (Sigma Aldrich Corp., Missouri, USA). A specialty polymer, Genomer 1231 (RAHN AG, Switzerland), a bifunctional acrylic resin, was used as well as a photoblocker, 2,2’-(2,5-thiophenediyl)bis(5-tert-butylbenzoxazole) (Benetex OB Plus or OB+) (Mayzo, Georgia, USA), and a photoinitiator, diphenyl(2,4,6-trimethylbenzoyl)phosphine oxide (TPO) (RAHN AG, Switzerland). Major equipment includes an Elcometer 224 Digital Surface Profile Gage (Elcometer Inc, Michigan, USA) and a MDX-40 Benchtop Computer Numerical Control (CNC) Mill (Roland Corp., Japan). An UVX Ultraviolet Intensity Radiometer (Analytik Jena US, California, USA) was used as well. Ultraviolet light emitting diodes (UV-LEDs) can be bought at any standard retailer. Finally, a CTC 3D-printer (Zhuhai CTC Electronic Co., LTD, China) and a MoonRay 3D-printer (SprintRay, California, USA) were used to print multiple tools throughout the experiment.

3D-printing and fabrication

All 3D-printed objects were designed via SketchUp (Google, California, USA). A coating station (Figure 2 a-b) was 3D-printed from polyethylene terephthalate (PET) using a CTC 3D-printer. The parts to the coating station include the ramp, the tray to hold the sample slides, the tray holder, a coating applicator, and collection vats for excess PDMS to be recycled.
Electric circuits were fabricated on printed circuit boards (PCB) on an MDX-40 benchtop mill, and eight UV-LEDs were tinned and soldered on each PCB. Five different types of LEDs were used in this experiment: 1.8 mm round bulb, 2 mm flat bulb, 2 mm round bulb, 3 mm flat bulb, and 3 mm round bulb. The PCBs were incorporated into 3D-printed UV curing stations (Figure 2 c-d) at various heights ranging from 2 to 10 cm. Each set of LEDs were characterized for light intensity over the 2- to 10-cm height range using the UVX Ultraviolet Intensity Radiometer. Each LED was turned on for approximately 30 s while the radiometer measured the intensity at each height. The intensity characterization led to proper dosages for UV curing.

Figure 2. 3D-printed tools. (a) Coating station printed from PET with printed applicator. The applicator is coating the PDMS mixture on the microscope slides. (b) Coating station with applicator separately. (c) 3D-printed UV-curing station with incorporated LEDs. Polymer slide sample would lie underneath the UV light source. (d) PCB with 8 LED light sources surrounding a port for a resin injector for fused deposition modeling (FDM) 3D-printing.
PDMS sample preparation and analysis

For the experiment, the PDMS pre-polymer was mixed thoroughly with the curing agent at a 10:1 ratio by mass and degassed for 30 min. The mixture was poured on the coating station over the glass slide tray. The applicator was used to spread the mixture, one pass in each direction, over 5 glass slides at 1000-µm layer thickness. To remove the slides, a punch block was used to push the slides out of the tray. Then the slides were manually put onto the stencil sheet. Each slide was then put on a printed stencil sheet in a 3 X 5 array (Figure 3) and placed in the oven to cure for 60 min at 75°C. Each stencil shows a map of 10 points throughout the slide used for measuring the change in film thickness and the surface profile in response to curing. An Elcometer 224 Digital Surface Profile Gauge was used to measure the layer thicknesses 24 h after curing. When we move on to the UV-curing portion, the procedure will remain relatively the same. One difference will be the use of photoinitiators in the PDMS mixtures. Each mixture will be adapted from various studies. The other difference is the samples will be placed in the fabricated UV curing stations for 30 s. This procedure assumes one is working with PDMS, but

![Printed stencil sheets in a 3X5 array (a) and one printed stencil sheet in close-up (b) showing the map of 10 points to measure average layer thicknesses.](image)

Figure 3.
the same procedure can be used for other polymers as well. The samples should be stored in amber glass containers to prevent premature UV curing.

**Acrylic resin sample preparation**

Genomer 1231 (the acrylic resin), OB+, and TPO were mixed together to make 4 separate 80 g samples varying only the weight percentage of TPO. Each sample consisted of approximately 98 wt% Genomer 1231, 0.05 wt% OB+, and 4 different weight percentages of TPO (0.5, 1.0, 1.5, and 2.0 wt%). The samples were stored in amber glass containers to prevent premature UV curing.

**Acrylic resin cure depth and cure time analysis**

To determine the necessary layer cure time of the specialty polymer, a 3D-printing test was used. The layer cure time is the amount of set time the printer allows to cure each cross-sectional layer of an object. The test included printing 3 objects using the MoonRay 3D-printer: a plain circle, a curing analysis scale, and micropatterned tiles with individual patterns (Figure 4).

---

**Figure 4.** 3D-printing test from Genomer 1231. (Left) Curing analysis scale individual parts. The numbers on the scale indicate if the layer cure time is sufficient or not. (Right) Micropatterned tiles with individualized patterns to indicate how well the printer can handle complex shapes under the varying conditions (Top row left to right) Honeycomb pillars, supports, horizontal channels, (Center row) vertical hollow pillars, positive cube pattern, positive letter pattern, (Bottom row) micropillars, negative cube pattern, negative letter pattern.
A circle of was cured for 30 s to measure the cure depth. UV light intensity and exposure time was held constant for all experiments, so only TPO concentration varied. Each TPO concentration produced circles of varying thicknesses representing the cure depth. The layer thickness was measured using a microcaliper.

The curing analysis scale and tiles were both printed with 50 µm cross sectional layers. The cure times for these layers were varied to obtain the optimal layer cure time for each TPO concentration. Varying the layer cure times allowed us to determine the ideal layer cure time for the best quality print. The curing analysis scale is a slide scale, of our own design, from 1-5, in increments of 1, indicating how well the sample is cured by indirectly measuring its shrinkage and dimensional accuracy. Based on the reading, we adjusted the cure time as shown in Table 1. Referencing to Figure 4, one part of the curing scale slides across the number line and will experience resistance based on the amount of shrinkage in the polymer after curing. If there is too little shrinkage, there will be resistance around 4 or 5. This means that the object is under-cured, and the cure time must be increased. If there is too much shrinkage, there will be a lot of resistance around 1 or 2. This means that the sample is over-cured, and the cure time must be decreased. A 3 indicated that both cure time and shrinkage was sufficient, so it was well-cured.

<table>
<thead>
<tr>
<th>Scale Reading</th>
<th>Physical Characteristic</th>
<th>Time Adjustment (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Largest shrinkage and largest resistance</td>
<td>Decrease by 6 to 10</td>
</tr>
<tr>
<td>2</td>
<td>Large shrinkage and large resistance</td>
<td>Decrease by 1 to 5</td>
</tr>
<tr>
<td>3</td>
<td>Sufficient shrinkage and resistance</td>
<td>No Change</td>
</tr>
<tr>
<td>4</td>
<td>Low shrinkage and low resistance</td>
<td>Increase by 1 to 5</td>
</tr>
<tr>
<td>5</td>
<td>Lowest shrinkage and lowest resistance</td>
<td>Increase by 6 to 10</td>
</tr>
</tbody>
</table>
When printing, a 15s cure time for 50 µm thicknesses was the starting point. Depending on the results of the scale for that trial, the cure time was manipulated. Once all cure depths and cure times were recorded, a plot was generated and set to a second order polynomial trendline (11) because the light penetration cannot be modelled linearly due to the cured polymer layers on the top blocking the light from penetrating to the lower levels. At a certain concentration of TPO, the cure time will reach a minimum point on the plot of cure time versus concentration. When the concentration increases after that optimal point, the cure time will increase again. This is due to the overall reaction mechanism (11).

The tile patterns were another way to look at how well the polymer cured. A standard tile structure was compared to the ones printed from the acrylic resin. When the tiles were under-cured, the intricate structures were flimsy, and the intricate details were indistinguishable as they were fused together. When the tiles were over-cured, the structures were very brittle, and the material lost flexibility. Based on how the intricate structures compare to the standard structure, we could determine how well the polymer layers were cured in addition to using the curing scale.

This procedure can be used with the PDMS as well, but the main purpose of this project is to prove that the coating/UV curing stations can work just as well and reduce the cost and time of developing a UV-curable polymer.
CHAPTER 3

RESULTS AND DISCUSSION

Surface profile of PDMS slides using thermal curing

The average layer thickness was found for 13 PDMS slides overall and individually after thermal curing for 60 min. 2 slides out of the total 15 were excluded from the calculation because there was too much sample loss before placing in the oven. The average layer thickness of each individual slide and the overall average can be found in Table 2. Percent deviations for individual slides were calculated from the 10 points across the same slide. The average standard deviation at the end is for all 130 points.

<table>
<thead>
<tr>
<th>Slide</th>
<th>Layer Thickness (µm)</th>
<th>Percent Deviation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>476.0</td>
<td>± 13.0</td>
</tr>
<tr>
<td>2</td>
<td>444.2</td>
<td>± 6.0</td>
</tr>
<tr>
<td>3</td>
<td>437.8</td>
<td>± 22.0</td>
</tr>
<tr>
<td>4</td>
<td>472.4</td>
<td>± 5.5</td>
</tr>
<tr>
<td>5</td>
<td>471.5</td>
<td>± 9.0</td>
</tr>
<tr>
<td>6</td>
<td>399.7</td>
<td>± 10.0</td>
</tr>
<tr>
<td>7</td>
<td>444.3</td>
<td>± 9.0</td>
</tr>
<tr>
<td>8</td>
<td>457.1</td>
<td>± 5.0</td>
</tr>
<tr>
<td>9</td>
<td>540.2</td>
<td>± 7.0</td>
</tr>
<tr>
<td>10</td>
<td>496.8</td>
<td>± 7.0</td>
</tr>
<tr>
<td>11</td>
<td>447.1</td>
<td>± 13.0</td>
</tr>
<tr>
<td>12</td>
<td>409.9</td>
<td>± 12.0</td>
</tr>
<tr>
<td>13</td>
<td>381.2</td>
<td>± 24.0</td>
</tr>
<tr>
<td>Average</td>
<td>452.2</td>
<td>± 11.0</td>
</tr>
</tbody>
</table>

From the table, the average layer thickness across all slides is 452.2 µm ± 11%. This means that the coating station system we used with the round bottom applicator produced flat surfaces. The flat surfaces will allow for uniform curing and easier calculations of cure depth.
Because the coating station can produce flat surfaces, it can be a suitable mass sample production method for testing the UV-curability of polymer formulations. However useful the system is, there is still room for improvements. The system would benefit from a better method for keeping the sample mixtures on the glass slide when removing the slide from the tray as seen by the 2 samples that were excluded from the calculations due to loss of material from the slide.

**UV-LED intensity characterization**

The intensity map for each of the 5 UV-LEDs from 2-10 cm can be found in Figure 5. The reason for the 2-10 cm range is to have a more accurate understanding of the UV intensity during the printing process. When we reach the point of adapting our FDM printer for UV-curing, the initial distance between the light source and the first layer would be about 2 cm. As the object is printing, the light source and the first layer on the build plate will grow farther apart. Knowing the intensity at farther distances will allow us to determine the dosage and its effect on the bottom layer of the object being built. For this study, a microfluidic device will be the object being built. Dosage was proportional to both the UV intensity and the exposure time and is expected to impact how well the PDMS cures (11,12). A too high dosage can lead to over-
curing, and the PDMS would lose its characteristic flexibility and optical clarity. Too low a dosage would prevent full curing and proper layering.

![Graph showing UV intensity vs distance for different UV-LED types.]

**Figure 5.** UV intensity in microwatts/cm² versus distance from source (cm) for different UV-LED types.

**Cure depth analysis**

The cure depth was recorded for every weight percentage of TPO and is included in Table 3 and plotted in Figure 6.

<table>
<thead>
<tr>
<th>Table 3. Cure Depth for Each Concentration of TPO</th>
</tr>
</thead>
<tbody>
<tr>
<td>wt% TPO</td>
</tr>
<tr>
<td>Cure Depth (µm)</td>
</tr>
</tbody>
</table>
When the concentration of TPO increases, the cure depth increases as well, up to the optimal concentration of TPO that produces the highest cure depth. At the optimal TPO concentration, the cure depth will reach a maximum value and then reverse as the concentration of TPO increases (11). The optimal cure depth occurred when the TPO concentration was approximately 2%. This pattern occurred due to the top polymer layer reflecting the UV light. At the lower concentrations, the top polymer layer would cure due to an immense amount of monomer, but then the light wouldn’t be able to penetrate deeper. The benefit of finding the optimal cure depth is not only to find the optimal number of layers for a printed object (11) but also to examine the extent to which the resin has polymerized. A low cure depth means weaker mechanical properties, such as strength, because the cross-linked polymers are not as fully bound together. This would mean that the object is under-cured. On the other hand, if the object is over-cured, it could lose other properties, such as flexibility or optical transparency.

**Figure 6.** Plot of the cure depth versus TPO concentration. The trend follows a quadratic pattern. With increasing amount of TPO, cure depth increased.
Layer cure times for acrylic resin

The optimal layer cure time for each concentration of TPO can be found in Table 4 and plotted in Figure 7. From the table, it is evident that the layer cure time will decrease with increasing TPO concentration. The rate of polymerization increased because there was more photoinitiator present.

<table>
<thead>
<tr>
<th>wt% TPO</th>
<th>0.5</th>
<th>1.5</th>
<th>2.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cure time (s)</td>
<td>25.0</td>
<td>10.0</td>
<td>6.0</td>
</tr>
</tbody>
</table>

As the TPO concentration is increased, the layer cure time acts in accordance to a non-linear second order polynomial (11). This is also due to the availability of the TPO catalyst and the optimal penetration of the UV light as shown from the cure depth. The printer allows for a set of time for each layer to cure according to the user’s input. Based on the inputs in this experiment, the previous relationship between the concentration and the layer cure times were determined. Determining the ideal layer cure time affects the time to print and the quality of the
printed object. A lower concentration of TPO can lead to longer cure times because the catalyst is not available to as many monomers. The longer exposure to the UV light allows for just enough excitement to start the polymerization reaction and produce a well-cured layer. However, the higher concentrations of TPO produced prints of equal quality but at faster times up until an optimal value around 2%. The difference between the time it took to print an object with 0.5wt% TPO and 2wt% TPO was approximately 30min. The higher availability of the catalyst allowed for a quicker propagation of the polymerization reaction. However, at even higher concentrations beyond the optimal value, the cure times will start to decrease again (11). This optimal value for TPO concentration allows for the best quality prints in the optimal amount of time.
CHAPTER 4

CONCLUSION AND FUTURE WORK

The research presented here is preliminary. One of the overall goals of this research is to develop a method for testing possible formulations for UV-curable resins to be used in 3D-printing. In addition, the other goal is to apply this method to developing a formulation for UV-curable PDMS for direct 3D-printing of microfluidic devices.

So far, it has been determined that 3D-printing is a valuable tool for research. A coating station was successfully 3D-printed to create uniform and flat PDMS slide samples for curing experiments. This procedure for the preparation of samples is meant to be applied to any potential polymer resin formulation. This quick and facile method of resin sample preparation is another step to a mass assay of photocurable and 3D-printable polymers. Another benefit of this coating procedure is the flat surfaces it produces. Flat surfaces allow for uniform curing and a simple platform to determine cure depth and cure time, both being important parameters to optimize for 3D-printing.

In addition to the coating station, the UV-curing stations are another example of how 3D-printing and other fabrication techniques are lucrative in designing research experiments and tools because of the potential for creative apparatus designs. In addition, the use of multiple types of LEDs shows how this system can be customizable for individual resins based on the effect of the varying dosages. Currently, the UV-curing system consists of 14 UV-curing stations, and we are improving upon incorporating multiple curing stations into one circuit for a one-step, mass assay of UV-curable resin formulations. At the moment, we are able to turn on 4 UV-curing stations at once. Using the curing station assay, we would be able to repeat cure depth
and cure time experiments without the time-consuming process of continuously printing the circle and curing analysis scale.

The results from the cure depth and cure time experiments showed an optimal resin formulation with 2wt% TPO. Knowing the cure depth and layer cure time for a polymer resin would help optimize the 3D-printing process, especially in manufacturing. Printing an object, or multiple objects, in less time without sacrificing mechanical and chemical properties would improve the design to implementation life cycle, the cost of manufacturing, and the purchase cost. Industries such as aerospace, biomedical, and automotive, to name a few, would benefit from the higher production rates and lower production costs. In this research, we are especially looking toward improving the design to implementation life cycle of microfluidic devices. Microfluidic devices are beneficial in fields such as point-of-care diagnostics (1), drug development (2), and chemical manufacturing (3), and more. Because the application of microfluidics is so wide-spread, the adoption of 3D-printing into microfabrication and manufacturing could significantly increase the convenience and practicality of microfluidic devices to facilitate implementation in applications such as improving diagnosing HIV (13) or fabricating organ-on-a-chips (14) to reduce or replace animal testing for drug screening.

Although the future holds exciting possibilities, there is still work to be done for this project. First, the data we have for surface profiles are for pure thermal curing. The next step is repeating the same procedure with photoinitiators added into the formulations. Photoinitiators that have been identified as possible candidates for UV-curable PDMS are 2,2-dimethoxy-2-phenyl acetophenone (DMAP) (15), thioxathen-9-one (16), Irgacure 651 (16), Irgacure 2100 (17), and 2-hydroxy-2 methylpropionophenone (18). The resin formulations will be placed in the UV-curing stations for periods ranging from 5 s to 60 s to determine how effective each LED is
in curing. After data collection, the ideal LED/resin combination will be used to adapt a 3D-printer to print using that combination.

In addition to the LED/resin combinations, the depths of cure and the layer cure times of both the PDMS resins and the Genomer 1231 resins will be determined using the coating station and UV-curing stations. The cure depths and layer cure times for the Genomer 1231 from the method previously done will be compared to those calculated using the coating station/UV-curing station method. The depths of cure and layer cure times should be similar to those already found. The same formulations will be used in addition to concentrations higher than 2wt% in order to obtain a proper relationship between TPO concentration and cure times. If the results from the coating station/UV-curing station method match the results from the UV-curing method using the MoonRay printer, then we can conclude that the coating station/UV-curing station method is a viable option for testing possible formulations and parameters for 3D-printing with UV-curable resins.

So far, we have done thermal curing experiments on a silicone-based polymer, PDMS, and UV-curing experiments on a bifunctional acrylic acid ester, Genomer 1231. In the future, we plan on experimenting on a trifunctional polymer to compare how functionality and structure affect the cure depth and cure times. Because of the customizability of the new method, future experiments with this method could be used to compare the polymerization kinetics of proprietary polymers to be used in 3D-printing.

The overall goal of this research is to be able to directly 3D-print microfluidic devices using UV-curable PDMS. So far, a microfluidic device has been designed with one channel on SketchUp with the following dimensions: 500 µm diameter channel, 3 cm length, 1.9 cm width, and 0.6 cm height. This simple design will be used to test how well the optimal resin
formulations for each polymer can print microfluidic devices. Then, the printed microfluidic device will be subjected to varying solvent-resistance testing outlined in Lee et. al. (19). Methanol, ethanol, and acetone are mainstream solvents to be used in this assay. Microfluidic devices should be resistant to multiple kinds of reactions depending on their application. The diversity of applications of microfluidic devices should reflect in the diversity of materials available to fabricate them. Our new method could provide other scientists and engineers with that flexibility to design their own materials at a lower cost for testing and adapt their 3D-printers in such a way to be able to customize their own microfabrication process, again, at a lower cost. This method is supposed to be simple to adopt by anyone, so a degree in engineering will not be a requirement to be able to print a microfluidic device for their own research purposes. In the future, this research could facilitate progress in on-site, microfluidic fabrication in hospitals and research labs around the world. It may be possible that a doctor or nurse could 3D-print microfluidic devices for HIV diagnostics or a biologist or pharmacologist could 3D-print a microfluidic organ-on-a-chip for drug testing. The range of possible applications are endless.
REFERENCES


