Spring 2022

Application of SLA 3D Printing for Polymers

Taylor Wilson
tlw156@uakron.edu

Recommended Citation

Wilson, Taylor, "Application of SLA 3D Printing for Polymers" (2022). *Williams Honors College, Honors Research Projects*. 1490.
https://ideaexchange.uakron.edu/honors_research_projects/1490

APRIL 22, 2022

APPLICATION OF SLA 3D PRINTING FOR POLYMERS

HONORS RESEARCH PROJECT, DEPARTMENT OF CHEMICAL ENGINEERING
4200:497-002

TAYLOR WILSON

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Abstract

Stereolithography is a type of 3D printing that allows liquid photopolymer resin to be cured into layers that make up a 3D object. Creation of such resins for these purposes can require a significant amount of time to test and develop, and commercial resins also require some amount of testing for printer settings before use. This paper reviews how stereolithography works, the materials used, and experimentation done to compare the resin properties to the determined curing times. Using several commercially available resins, varying base exposure and layer exposure times were used to determine the lowest possible curing time that gave the best results. The ideal curing times were compared to certain properties of the resin to determine key trends and found that viscosity had a significant effect on the curing time. This trend can be used to develop a method of finding the ideal curing times for a resin much faster than current testing methods. Certain aspects of the final samples were also noted, and ideal resin monomers are recommended for flexible or crystalline objects, or simply the fastest curing or production speed.

Executive Summary

Stereolithography, or SLA, is a type of 3D printing in which a photosensitive resin is cured into layers by UV light. This method of 3D printing has some advantages over other methods, including achieving a higher amount of detail in objects and creating less waste. The photosensitive resins that is used for SLA printing are now available in a variety of properties, but with the variety comes a wide range of parameters to change in order to get a decent result. The photosensitive resins are comprised of four main components: monomers, solvents, photoinitiators, and additives. The resin is able to be cured by UV light by means of the photoinitiator, in which free radicals are created and react with the monomers to create the polymer chains and cure the resin. The solvent is used to adjust the monomer concentration, which will affect the reaction rate. Additives like pigments or fillers are added to the resin to give the cured product a better appearance or better mechanical properties. Commercially available resins often offer recommended settings for their material to be used, but these can sometimes be unreliable or are unavailable. Using the resin properties to determine the ideal parameters, or an initial guess would greatly reduce or eliminate the amount of time spent testing each resin before actual usage. This would especially be beneficial in cases where recommended settings are unavailable, such as in the development of a new SLA resin.

For the experimentation, an Anycubic Photon S SLA printer was set up and used to carry out the tests. A range of base exposure and layer exposure times were tested for each of seven total photosensitive resins. The different resins were chosen based on properties, material components, and their weight percentages. The results from each set of tests were recorded and compared to the given recommended settings for each resin. Successful tests were determined by criteria such as the print stuck to the plate for the duration of the printing session, the print was not “easy” to

remove from the plate, little to no “flash” is evident on the plate after removal, the 3D printed object is whole (no parts missing before removal), the print shows significant resemblance to the 3D model, and there are no significant defects in the print before removal.

From testing, several trends could be observed by plotting the resin properties or components against the exposure results. By comparing two resins directly, it was determined that the opacity or color of the resin had no effect on the curing time. The resin’s viscosity gave the best trend when plotted against the base and layer exposure times, and a trendline function was created. It would be possible to use the viscosity of the resin to predict the ideal base exposure and layer exposure times using these equations. The monomer type and weight percentage were also plotted with the results, but no significant trends were found.

For faster printing, it is recommended to use a low to medium viscosity resin and avoid high viscosity resins. The most durable results used hexamethylene diacrylate and isooctyl acrylate monomers and are therefore recommended in cases where durability is prioritized. These monomers are also recommended in cases where production speed is prioritized. In cases where polymer flexibility is needed, E03TMPTA monomer is recommended but requires a higher curing time. In general, it would be recommended to use resins that contain the following weight percentages: 5% photoinitiator, 40-50% monomer, 40-50% solvent, and no more than 5% additives. It is important to use photoinitiators, solvents, and additives that work with the chosen monomer. It is also possible to use a combination of monomers to achieve unique mechanical properties in the final product.

Based on these experimental results, it would be possible to develop new photopolymer resins with more ease than current methods. The testing of several monomers and weight percentages allows for discarding of monomers that will not achieve the desired effects, and allow developers are researchers to begin testing with proper monomer types, reducing the amount of testing time. Using the discovered viscosity trend to find the predicted curing times will also speed up the amount of time needed to test the resin and find whether it is fit for stereolithography. These findings could be used by individuals or companies developing these resins, or those simply using commercial resins that do not provide recommended settings. The future of this research should be to continue testing resins to further develop the found trend and use other testing criteria to find more possible trends in resin testing, as well as develop new resins more quickly and accurately for special applications.

This project has helped me better understand the topic of 3D printing as a whole, and specifically stereolithography with its advantages and disadvantages. I will be able to apply the knowledge and skills gained from testing and research on this topic in future relevant areas. In doing these experiments I learned to develop unique testing procedures and criteria, a skill that will be most useful in research and development. Other important skills that I will be sure to utilize in the future include data analysis, specialized researching, and problem solving. This project has also helped me be more and think more creatively in other subject areas, and it has helped me understand and think about topics in ways I would not normally do so. Due to this project, I plan to continue doing research and testing on my own behalf in the area of 3D printing in the future.

Introduction

3D printing is a revolutionary technology that is now widely used for a variety of applications. 3D printing, also known as additive manufacturing, refers to the use of a three-dimensional digital model in construction by computer-controlled means to create an object, especially those that would be impossible to create by other means [1]. 3D printing allows for hollow or complicated internal structures to be created in the object, reducing the weight of the print, and also saving material [2]. While 3D printing takes much longer than other types of molding, it produces much less material waste in the process. Some types of 3D printing include Stereolithography (SLA), Selective Laser Sintering (SLS), Fused Deposition Modeling (FDM), Digital Light Process (DLP), Multi Jet Fusion (MJF), and Direct Metal Laser Sintering (DMLS) [3], where FDM is the most common method used today [4]. It is now common for not only industries but also consumers to have a 3D printer at home for small projects.

Stereolithography, or SLA, is the first method of 3D printing to be used, developed by Charles Hull [5]. Also known as Vat polymerization, the process involves curing liquid resin material layer-by-layer on a moving build plate to create a 3D object [6]. This method in particular has some key advantages over other methods of 3D printing [7]. SLA uses very thin layers compared to other processes, meaning it is possible to achieve a greater amount of detail in the print. Since the entire layer is cured at the same time, the printer is not limited by an extrusion time, and therefore becomes faster than other methods with larger or wider objects. Also due to the layer curing method, not as many support structures are needed in SLA printing. Although, the liquid resin, depending on the material, can emit harmful odors or is toxic when in contact with skin, making it less safe to use than materials in other forms of 3D printing. SLA printing also requires an intensive cleaning and post-curing process that may not be ideal for the object being created [8].

There is now a wide range of materials that are able to be used in SLA 3D printing. With the wide range of materials comes a wide range of variables and parameters for processing, making it difficult to get a great result when just starting. Most resin suppliers provide recommended settings for these photosensitive polymer materials, but these are not always correct, or it may not be possible to use these settings based on the other parameters being used. This means it is often required to do extensive testing to determine the proper settings before being able to begin printing [9]. While this may not be an issue in the case that the resin will be used extensively and exclusively at the same parameters, it becomes more challenging when different parameters or resins are being used and switched out often. It becomes even more difficult in the development of these photopolymer resins, in which no “recommended settings” are available. In these cases, it would be beneficial to find an initial guess for these settings based on the materials or properties of the resin to save time in the initial use of the resin or the development of new resins. The goal of this project is to test commercial resins that have different properties and components, compare the recommended settings to the ideal settings found from testing, and determine if there are trends between the resin properties or components and ideal settings. Ideal components and component ratios for the resin can also be determined from these experiments based on two main goals in printing: faster processing, and more durable material for objects.

Background

Stereolithography, or SLA, is the process of curing a liquid photosensitive polymer by the means of an ultra-violet light source that provides energy for a chemical, or curing, reaction [10]. SLA is also known as Vat polymerization, in which the liquid resin material is poured into a vat over a light-emitting screen. The vat has a transparent film on the bottom to allow the light to pass through. An aluminum build plate is used to hold the 3D object, which sits on an axis that allows the plate to be lowered into the vat and raised after each layer is cured, which means the 3D object is printed upside down [11]. The plate hovers very close to the bottom of the vat, which allows only a small amount of material between the plate and the screen, to cure a very thin layer. Common layer thicknesses range from 0.01 to 0.05 mm. When the plate is lowered, the screen of the printer displays the layer shape in UV light which cures the material into that shape without curing the surrounding material. The cure time for different resins can vary greatly and depend on the resin properties and/or components. Cure times can range from 3 to 15 seconds for common materials but can become much higher for specialty resins. Figure 1 shows a model of the main components of an SLA printer.

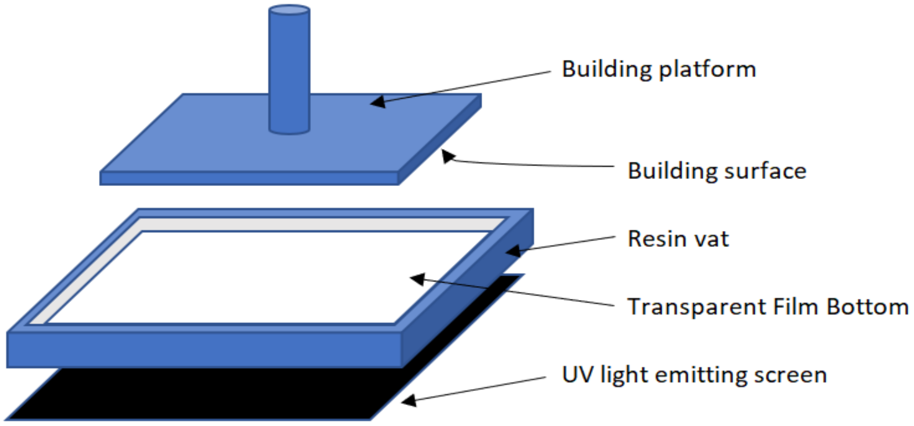


Figure 1: Model of the basic components in a stereolithography 3D printer.

The liquid photosensitive polymer resin is comprised of four main components: monomers, solvents, photoinitiators, and additives. The resin is able to be cured by UV light by means of the photoinitiator, which absorbs light that is typically in the 250 to 450 nm range [12]. The subsequent reaction creates free radicals in which the monomers in the resin react with, which performs a chain-growth polymerization reaction that creates polymer chains or crosslinks the chains and cures the resin [13,14]. The basic initiator, polymerization, and termination reactions are shown in Equations 1, 2, and 3, where I is the initiator, $R\cdot$ is a free radical, M is the monomer, and P_n and P_m are the polymer chains.

$$I \xrightarrow{k_d} 2R\cdot \qquad \text{(Equation 1)}$$

$$R - M\cdot + nM \xrightarrow{k_p} P_n - M\cdot \qquad \text{(Equation 2)}$$

$$P_n\cdot + P_m\cdot \xrightarrow{k_t} P_n + P_m{}^* \qquad \text{(Equation 3)}$$

The solvent is used to create a solution which adjusts the monomer concentration. The monomer concentration directly affects the overall reaction rate as shown in Equation 4, where R_p is the overall reaction rate, $[M]$ is the monomer concentration, $[I]$ is the initiator concentration, f is the reaction efficiency, and k_d, k_p, and k_t are the initiation, polymerization, and termination rate constants, respectively. The reaction rate greatly impacts the cure time of the resin, and it is therefore critical to have a proper ratio of solvent to monomer.

$$R_p = k_p[M]\sqrt{\frac{k_d f[I]}{k_t}} \qquad \text{(Equation 4)}$$

Additives used in the photopolymer resins mainly include pigments, which alter the final appearance of the printed object and may also impact the curing time due to opacity of the resin. Other additives include stabilizers or fillers that can enhance the properties of the cured resin.

Experimental Methods

Materials

A total of seven different resins were tested using the SLA printer. The resins were sourced from different 3D printing companies and are consisted of different types of monomers, solvents, photoinitiators, and additives, as well as different weight ratios of each of these components. Each of these components contributes greatly to the performance and properties of the resin. The resins were chosen based on the type of monomer and solvent, specific ratios of monomer and solvent, resin viscosity, and additives. Table 1 provides a summary of the component weight concentrations and properties of the resins tested [15,16,17,18,19].

Table 1: Table providing the name of each resin, the main components and weight percent of each main component, viscosity, and the marketed or visual qualities of the resin. Data for the weight percentages and viscosity were taken from the product safety data sheets (SDSs) or the supplier was contacted for the information.

Resin:	**Monomer (wt %):**	**PI (wt %):**	**Solvent/Epoxy (wt %):**	**Additives (wt %)**	**Viscosity (mPa*s):**	**Comments:**
Anycubic Resin, provided	isooctyl acrylate, 1,3-propanediyl diacrylate (45%)	phosphine oxide (TPO) (5%)	Propylidynetrimethanol, esters with acrylic acid (45%)	unspecified pigments/fillers (5%)	190	Translucent green color. Resin provided with printer.
ELEGOO ABS-like resin	hexamethylene diacrylate (40%)	hydroxycyclohexyl phenyl ketone (5%)	epoxy resin (50%)	unspecified pigments/fillers (5%)	210	Opaque gray resin, medium viscosity. Marketed as comparable to ABS polymer in FDM printing.
ELEGOO Water-washing resin	hexamethylene diacrylate (40%)	hydroxycyclohexyl phenyl ketone (5%)	epoxy resin (50%)	unspecified pigments/fillers (5%)	140	Transparent blue resin, very low viscosity, almost clear in apperance.
F69 Flexible TPU-like resin	4-acryloylmorpholine (15%)	phosphine oxide (TPO) (5%)	Acrylated aliphatic urethane (80%)	unspecified pigments/fillers (<1%)	980	Opaque black resin, very thick and had a bad odor.
iFun Toughness resin	E03TMPTA (30%)	phosphine oxide (TPO) (5%)	Polyester acrylate (60%)	unspecified pigments/fillers (5%)	350	Opaque white resin, marketed as durable and slightly flexible.
Wanhao flexible resin	4 different monomers (crosslinking) (50%)	phosphine oxide (TPO) (5%)	Bisphenol A epoxy diacrylate (45%)	unspecified pigments/fillers (<1%)	1080	Opaque black resin, very thick and had a bad odor.
Anycubic plant-based resin	isooctyl acrylate, 1,3-propanediyl diacrylate (45%)	2-methylpropan-1-one (5%)	Fatty acids, Soya, epoxidized, Bu Esters (45%)	unspecified pigments/fillers (5%)	190	Clear resin, same viscosity as provided Anycubic resin. Marketed as plant based, more sustainable and environmentally friendly.

Equipment and Procedure

An Anycubic Photon S SLA 3D printer was set up and used for the experiments. The printer build plate had to be properly leveled, as it is crucial to have an even layer thickness for printing. The LCD screen is calibrated by running an exposure test, which is run without the resin vat in place. To make sure the printer is working properly, the printer's test file was run with the provided photosensitive resin, and the result is given in Figure 2. Determining if the print is adequate is subjective, and the criteria for considering a sample "successful" is discussed later. Once the printer was properly assembled and calibrated, no further adjustments were required, and the same printer set-up was used for each resin test. The assembled Anycubic 3D printer is shown in Figure 3.

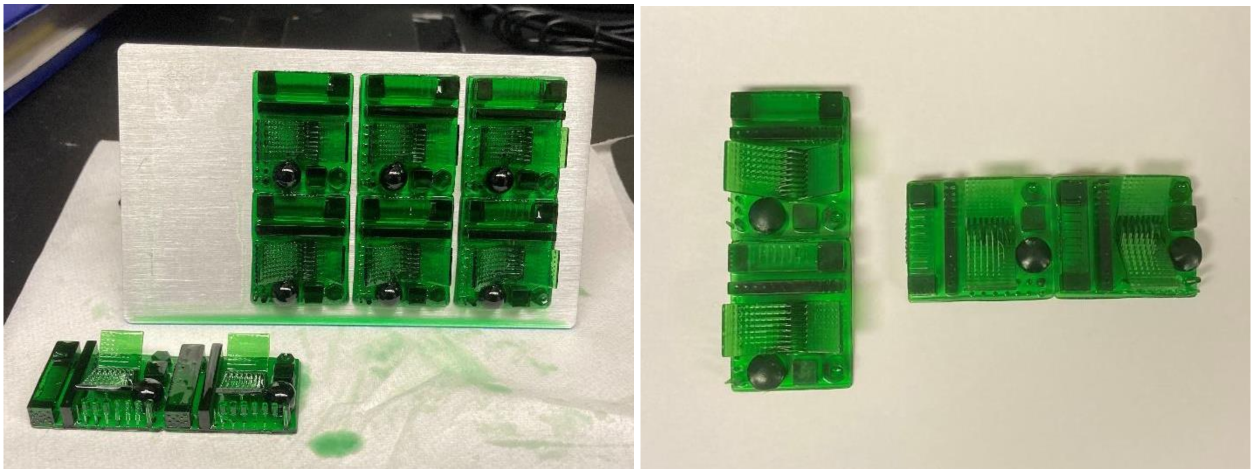


Figure 2: First test run of the printer during the set-up phase, using the provided printer resin and test file, using the default printer settings. The printed object here was considered to be successful.

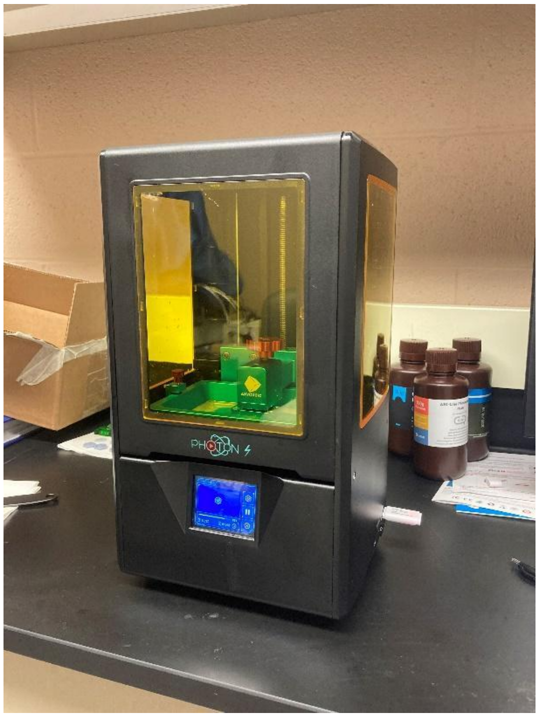


Figure 3: The set-up Anycubic Photon S 3D printer.

Each resin was tested to find the ideal base exposure curing time and ideal layer curing time. The layer curing time is the time required for the resin to harden in each layer throughout the printed object. The base exposure time is an adjusted time to allow further curing of the resin to ensure the 3D printed object adheres to the build plate. The base exposure time is much longer than the layer exposure time and is used only for the first few layers of the object's file. The default number of base layers is three, which was used for every resin test. The layer exposure times tested were 2, 6, 10, 14, and 18 seconds for each resin, using the resin's recommended base exposure time in each case. The base exposure times tested were 20, 40, 60, and 80 seconds for each resin, in which each case the resin's recommended layer exposure time was used. After each sample was printed, the bottom of the resin vat was scraped, and the build plate was cleaned to avoid cured resin interfering with the subsequent sample. It was important to scrape the bottom of the vat at the end of each run, especially in cases where the print did not stick to the build plate, in which the printer would cure some of the resin at the bottom of the vat. After each resin was tested, the resin vat was emptied and cleaned to avoid contamination between resins. Each printed sample was rinsed in a beaker of isopropyl alcohol to remove the excess uncured resin.

The test file used was a small hexagon with intricate details, shown in Appendix B. This file was chosen to easily distinguish between loss of detail and brittle or weak polymers and was reduced in size to make testing faster. This test file was used for every sample test to reduce the number of variables between each test.

Results

The results from performing the layer exposure and base exposure tests on each resin are summarized in Table 2. The ideal settings determined are compared to the recommended settings provided by each resin supplier if applicable. Important notes were recorded and are provided in the comments section.

Table 2: Summarized results of testing for base and layer exposure times for each type of resin. Recommended settings are shown to compare to ideal settings found in testing.

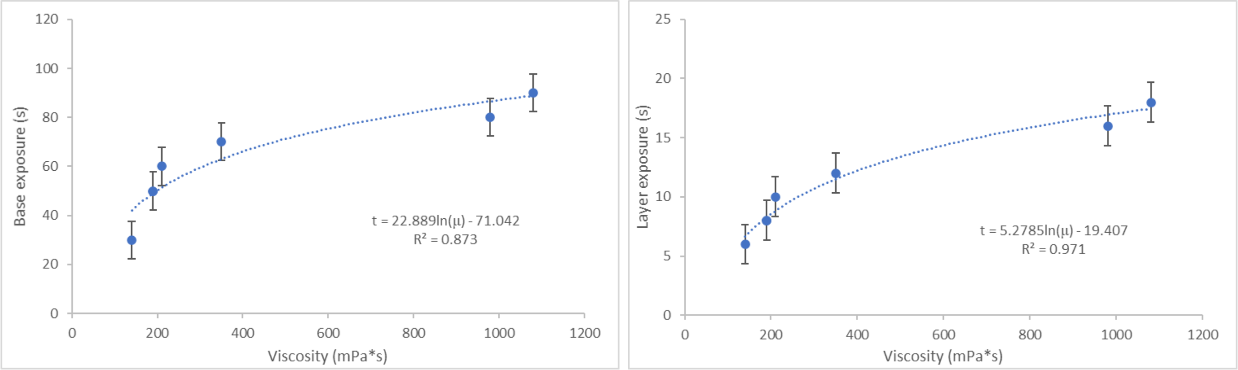
Resin:	**Recommended Settings (from supplier):**	**Ideal settings (from testing):**	**Comments from testing:**
Anycubic Resin, provided	60 s base 8 s layer	50 s base 8 s layer	Samples had good results near recommended settings. Samples had good durability.
ELEGOO ABS-like resin	60 s base 8 s layer	60 s base 10 s layer	Samples had good results near recommended settings. Slightly weaker/more fragile sample than Anycubic resin.
ELEGOO Water-washing resin	60 s base 8 s layer	30 s base 6 s layer	All samples stuck well to plate, but print was very weak, prone ot breaking or snapping.
F69 Flexible TPU-like resin	45 s base 10 s layer	80 s base 16 s layer	Did not print well at recommended settings, ideal times much higher. Would fail to print in areas, weak spots in finished print casued breakage.
iFun Toughness resin	Not available	70 s base 12 s layer	No recommended settings were provided for comparison. Had issues sticking to plate, but samples are relatively durable.
Wanhao flexible resin	Not available	> 80 s base 18 s layer	No recommended settings were provided for comparison. Very flimsy, seperation between printed layers.
Anycubic plant-based resin	60-80 s base 8-10 s layer	50 s base 8 s layer	Slightly differed from recommended settings, had same result as other Anycubic resin.

The 20, 40, 60, and 80 second base exposure times were tested for each resin. A successful print was determined as satisfying the following criteria: the print stuck to the plate for the duration of the printing session, the print was not “easy” to remove from the plate, and little to no “flash” is evident on the plate after removal. The print was considered easy to remove if little to no force was required to slide the scraping tool between the plate and the printed object. Flash refers to excess cured material around the plate or the printed object, and excess flash on the plate after removal indicates an over-cured sample. The print sticking to the plate for the duration of the print has the highest priority of the criteria. If the print was able to stick to the plate, but the sample required little force to remove, and the next sample had excessive flash, the ideal time was considered a half-step up from the first print that sticking was evident.

The 2, 6, 10, 14, and 18 second layer exposure times were tested for each resin. A successful print was determined as satisfying the following criteria: 3D printed object is whole (no parts missing before removal), the print shows significant resemblance to the 3D model, and there are no significant defects in the print before removal. The distinction for these criteria is made before the removal of the print from the plate because breakage resulting from removal may be at fault of the material's mechanical properties or improper technique, and thus should not be considered. Similar to the base exposure time, if during the layer exposure tests the print was whole, but the sample showed some defects, and the next sample began losing detail compared to the 3D model, the ideal time was considered a half-step up from the first print that printed whole.

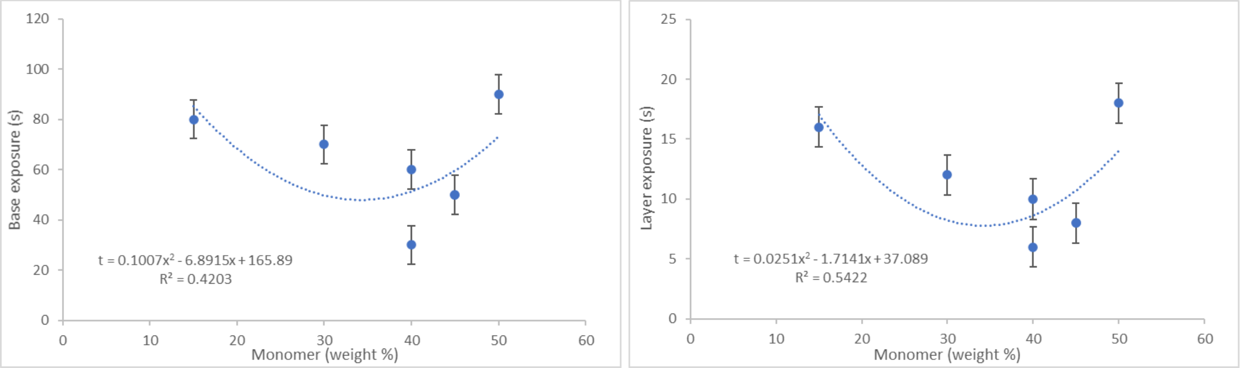
As shown in Table 2, the recommended resin settings were not always close to the ideal settings. In the case of the iFun Toughness resin and the Wanhao flexible resin, recommended settings were not provided. The Anycubic resins and ELEGOO ABS-like resin had ideal settings close to the recommended settings but still required some adjustment. The ELEGOO water-washing resin and F69 TPU-like resin had a large difference between recommended and ideal settings, in which the base exposure varied by over 30 seconds in each case and the layer exposure varied by 6 seconds in the case of the F69 TPU-like resin. From these results it is apparent the recommended settings are not reliable, and other means for determining ideal settings for SLA resins should be developed and implemented.

The ideal settings were compared to the resin properties and components to find possible trends. The ideal layer exposure and ideal base exposure were graphed against the resin viscosity (Figure 4), monomer concentration (Figure 5), and the type of monomer (Figure 6). The photoinitiator concentration, while a significant factor, is at a constant weight percentage throughout all of the tested resins, and therefore cannot be compared.



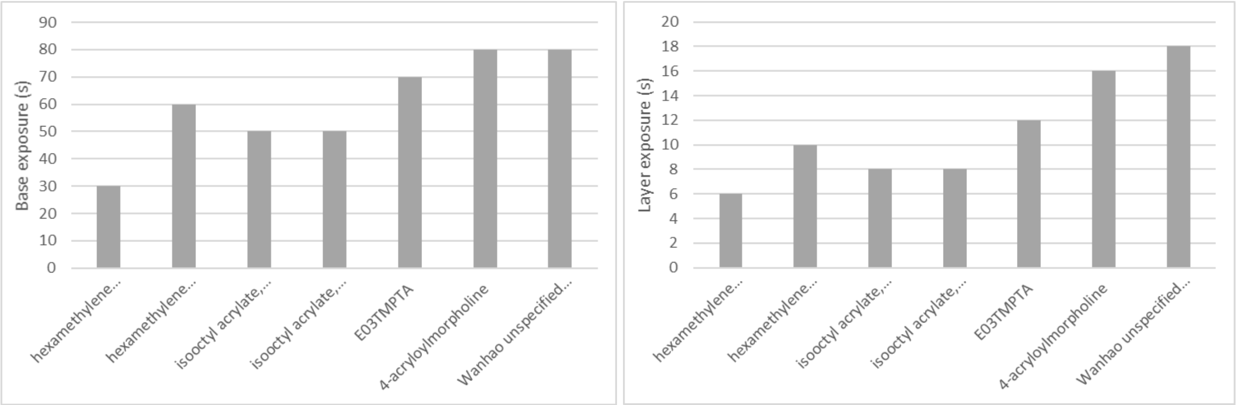
a) b)

Figure 4: Viscosity values plotted against the ideal base exposure times (a) and ideal layer exposure times (b). The best-fit trendline was added to the graph, and the trendline equation and R squared value are shown.



a) b)

Figure 5: Monomer weight percentages for each resin are plotted against the ideal base exposure times (a) and ideal layer exposure times (b). The best-fit trendline was added to the graph, and the trendline equation and R squared value are shown. Two resins had a monomer weight percentage of 40%, and therefore there are recorded times for this value.



a) b)

Monomer type:	**base exposure (s)**	**layer exposure (s)**
hexamethylene diacrylate	30	6
hexamethylene diacrylate	60	10
isooctyl acrylate, 1,3-propanediyl diacrylate	50	8
isooctyl acrylate, 1,3-propanediyl diacrylate	50	8
E03TMPTA	70	12
4-acryloylmorpholine	80	16
Wanhao - unspecified monomers	80	18

c)

Figure 6: The type of monomer in each resin is graphed showing the ideal base exposure times (a) and ideal layer exposure times (b). The base and layer exposure values for each monomer type are also displayed in table (c).

Pictures of the printed samples are provided in Appendix A. These show how the samples looked after removal from the build plate and key observations are listed in each description. The observation tables for each resin are shown in Appendix C.

Discussion and Analysis

It was determined from Table 2 that recommended settings are not reliable for immediate use and require varying amounts of adjustment. Therefore, Figure 4, Figure 5, and Figure 6 were created to compare the resin properties and components to the ideal processing times to find possible trends.

To make sure the different colors of resins did not affect the results, the two Anycubic resins were compared directly. As the two resins have the same viscosity and weight percentage of main components, the main difference between the two is the color and opacity of the resin. Comparing the two from Table 2, the two resins had the same ideal base and layer exposure times. From this test, it is evident that the opacity or color of the resin has no effect on the base or layer exposure time.

The viscosity plot shown in Figure 4 shows an adequate trend, in that as the viscosity increases, both the base and layer exposure times increase. This could be caused by the higher viscosity hindering the movement of the monomer in the resin, thus slowing the reaction. The data was fit with a regression that best fit the data, a logarithmic function, and the coefficient of determination for the base exposure and layer exposure regressions were 0.873 and 0.971, respectively. These values are relatively high and show the logarithmic regression is a good fit for the given data. The trendline equation for the base exposure and viscosity is provided in Equation 5, and the trendline equation for the layer exposure and viscosity is provided in Equation 6, where μ is the viscosity in mPa*s, and t is the exposure time in seconds.

$$t = 22.9 * ln(\mu) - 71.0 \qquad \text{(Equation 5)}$$

$$t = 5.3 * ln(\mu) - 19.4 \qquad \text{(Equation 6)}$$

The monomer concentration and monomer type trends, shown in Figures 5 and 6, were far less significant than the viscosity trend. The data was fit with a regression that best fit the data, a polynomial function of order 2, and the coefficient of determination for the base exposure and layer exposure regressions were 0.42 and 0.54, respectively. These values show the data does not have a significant trend, and both the monomer concentration and monomer type do not have a significant impact on the base exposure and the layer exposure times.

After the samples were removed from the build plate, notes about the flexibility of the samples were taken. If the samples were able to flex significantly without much force or without breaking, they were considered flexible. These samples were also rubbery to the touch and appeared to have a matte finish. If the samples snapped with significant force or resisted bending, they were noted as crystalline. These samples also had a glossy or shiny finish. This test is somewhat subjective, and results could vary depending on the discretion of others. This test is used only to recommend polymers based on the feeling of the final product, and no quantitative results were determined from this test.

It would be beneficial to do further testing in this area to confirm the validity of the results and trends described earlier. Larger ranges with smaller step increments in times would most likely lead to more accurate results. It is also suggested to compare other testing parameters such as the number of base layers and layer thickness to other material properties such as varying levels of photoinitiator or inclusion of different additives. The size of the 3D object to be printed may also affect printing results, and it would be recommended to do further research varying the size or angle at which the object is printed.

While outside variables were attempted to be minimized or eliminated, there were still several uncontrollable factors that may have led to errors in the results. The viscosity of the resin was shown to have a significant effect on curing times, which is a function of temperature. It is possible that temperature varied in the lab, and therefore caused discrepancies in the viscosity values. It is also possible that cross-contamination of resins may have occurred when switching between them. Due to the experimentation procedure's qualitative nature, the results are subjective, and opinions may differ.

Recommendations and Conclusions

Shown by the results, the viscosity of the photopolymer resin plays a major role in the curing times needed. It is recommended to use lower viscosity solvents for the monomers to reduce the overall viscosity of the resin. It is also recommended to use Equations 5 and 6 to determine preliminary times for testing resins, as these calculated times should be close or at the ideal curing times, thus reducing the amount of time needed to test.

Based on the results of testing, it is possible to determine the ideal range of resin component weight percentages, and recommended types of components or resin properties. For faster printing, it is recommended to use a low to medium viscosity resin and avoid high viscosity resins. The most durable results used hexamethylene diacrylate and isooctyl acrylate monomers and are therefore recommended in cases where durability is prioritized. These monomers are also recommended in cases where production speed is prioritized. In cases where polymer flexibility is needed, E03TMPTA monomer is recommended but requires a higher curing time. In general, it would be recommended to use resins that contain the following weight percentages: 5% photoinitiator, 40-50% monomer, 40-50% solvent, and no more than 5% additives. It is important to use photoinitiators, solvents, and additives that work with the chosen monomer. It is also possible to use a combination of monomers to achieve unique mechanical properties in the final product.

Acknowledgements

This research is supported by The University of Akron’s Williams Honors College and The University of Akron’s Chemical Engineering Department. Through the University’s financial and educational support, in-depth research on the topic of stereolithography and photopolymer resins was made possible by providing equipment, materials, and the laboratory facility.

This project would not be possible without the help of Dr. Qixin Zhou and Zichen Ling. Their knowledge and attention to detail is truly inspiring, and their helpful feedback and recommendations made this project what it is. I anticipate this work will help in their future research, and I thank them greatly for their help throughout the course of this project.

I thank those at The University of Akron for approving and accepting this research on behalf of the Williams Honors College, and those reading the contents of this paper and finding use in the work done in this project.

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Appendices

Appendix A: Sample Photographs of Each Test for Each Resin

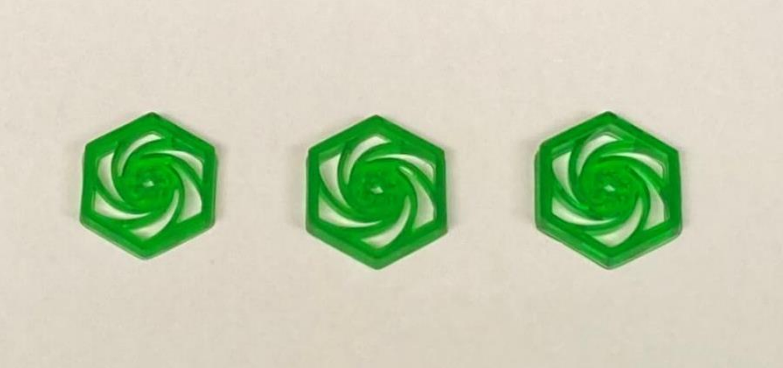


Figure 7: Photo of the results from the base exposure time tests for the provided green Anycubic resin. The 20 second sample did not stick to the plate and is therefore not pictured. The 40, 60, and 80 second samples are shown from left to right.

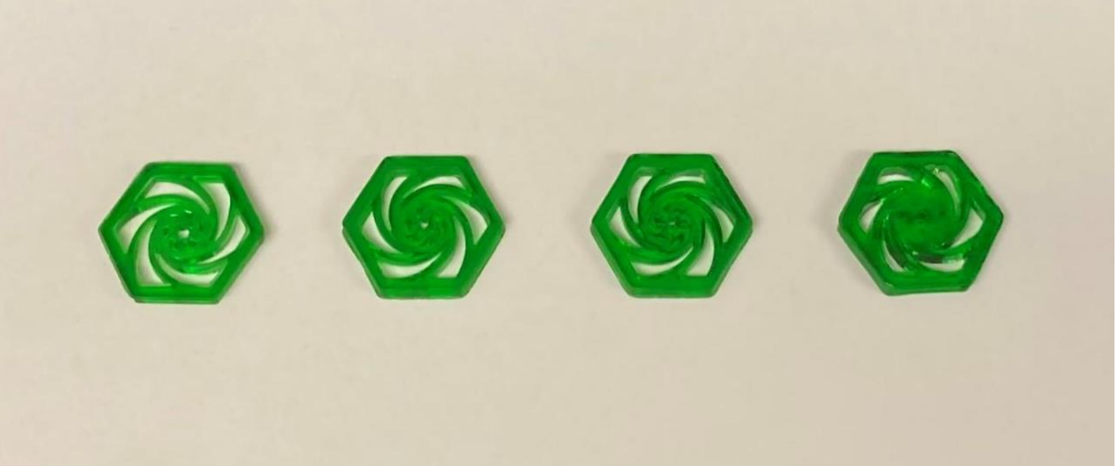


Figure 8: Photo of the results from the layer exposure time tests for the provided green Anycubic resin. The 2 second sample did not print and is not pictured. The 6, 10, 14, and 18 second samples are shown from left to right.

Figure 9: Photo of the results from the base exposure time tests for the blue ELEGOO Water-Washing resin. All prints are stuck to the plate, and the 20, 40, 60, and 80 second test samples are shown from right to left.

Figure 10: Photo of the results from the layer exposure time tests for the blue ELEGOO Water-Washing resin. The 2 second sample did not stick to the build plate and is not pictured. The 6, 10, 14, and 18 second samples are shown from left to right. The far-right sample easily shows an example of loss in detail, as the center holes of the object are no longer visible.

Figure 11: Photo of the results from the base exposure time tests for the gray ELEGOO ABS-like resin. The 20 and 40 second samples did not stick to the plate and are therefore not pictured. The 60 and 80 second samples are shown from left to right.

Figure 12: Photo of the results from the layer exposure time tests for the gray ELEGOO ABS-like resin. The 2 and 6 second samples did not stick to build plate and are not pictured. The 10, 14, and 18 second samples are shown from left to right.

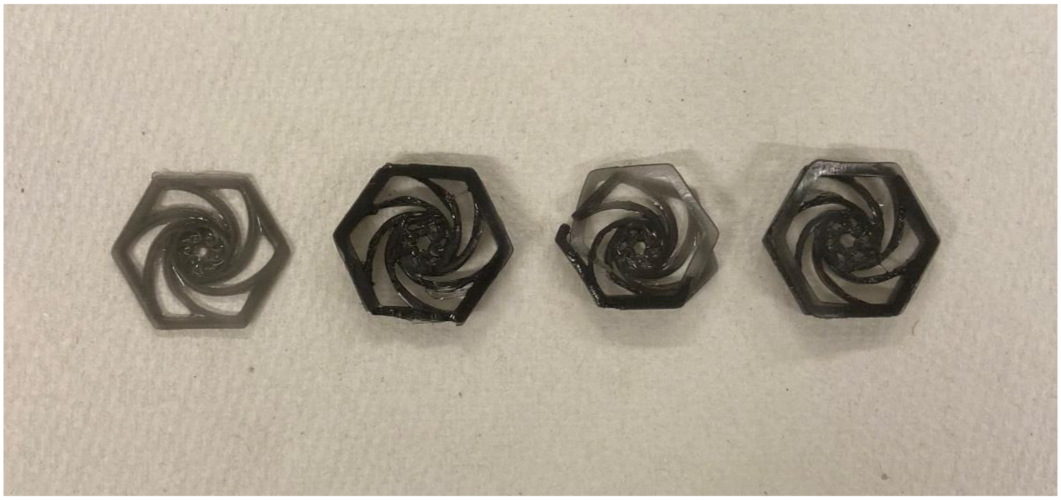


Figure 13: Photo of the results from the base exposure time tests for the F69 TPU-like resin. The 20, 40, 60, and 80 second samples are pictured from left to right.

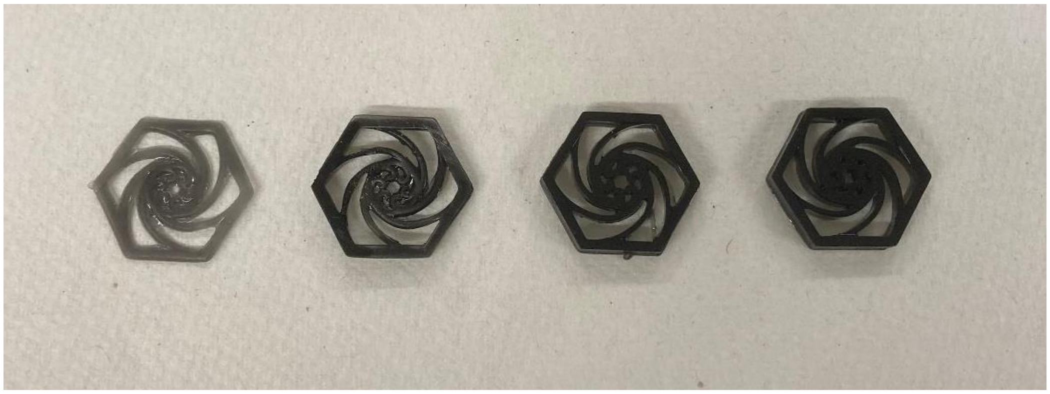


Figure 14: Photo of the results from the layer exposure time tests for the F69 TPU-like resin. The 2 and 6 second samples did not stick to the build plate. The 6 second sample is pictured on the left as an example of a failed print, and the result was salvaged from the bottom of the resin vat. The subsequent 10, 14, and 18 second samples are shown from left to right.

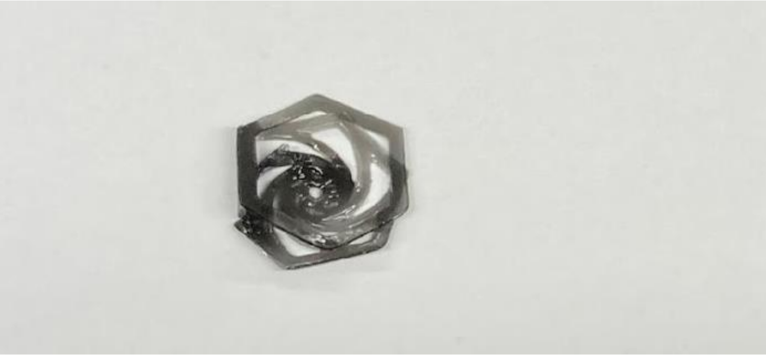


Figure 15: Photo of the results from the base exposure time tests for the Wanhao flexible rubber resin. The sample shown is the 80 second sample, and the 20, 40, and 60 second samples did not stick. The sample still was still very easy to remove, so each of the base exposure tests was considered failed.

Figure 16: Photo of the results from the layer exposure time tests for the Wanhao flexible rubber resin. The 2, 6, and 10 second samples did not stick to the build plate and are not pictured. The 14 and 18 second samples are shown, respectively. The 14 second sample had significant layer separation.

Figure 17: Photo of the results from the base exposure time tests for the iFun toughness resin. While all samples have significant defects, the 40, 60, and 80 second samples are shown from left to right.

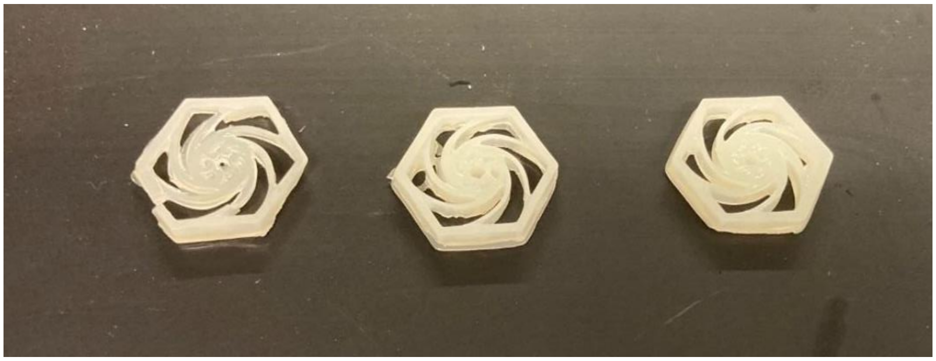


Figure 18: Photo of the results from the layer exposure time tests for the iFun toughness resin. The 2 and 6 second samples did not stick to the build plate and are not pictured. The 10, 14, and 18 second samples are shown from left to right.

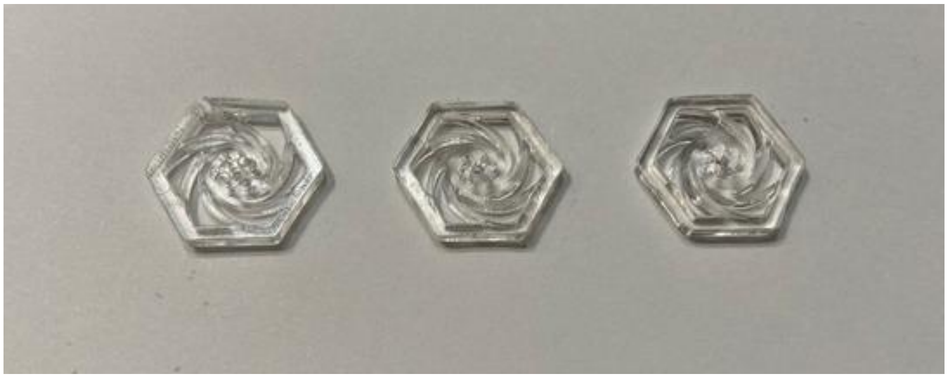
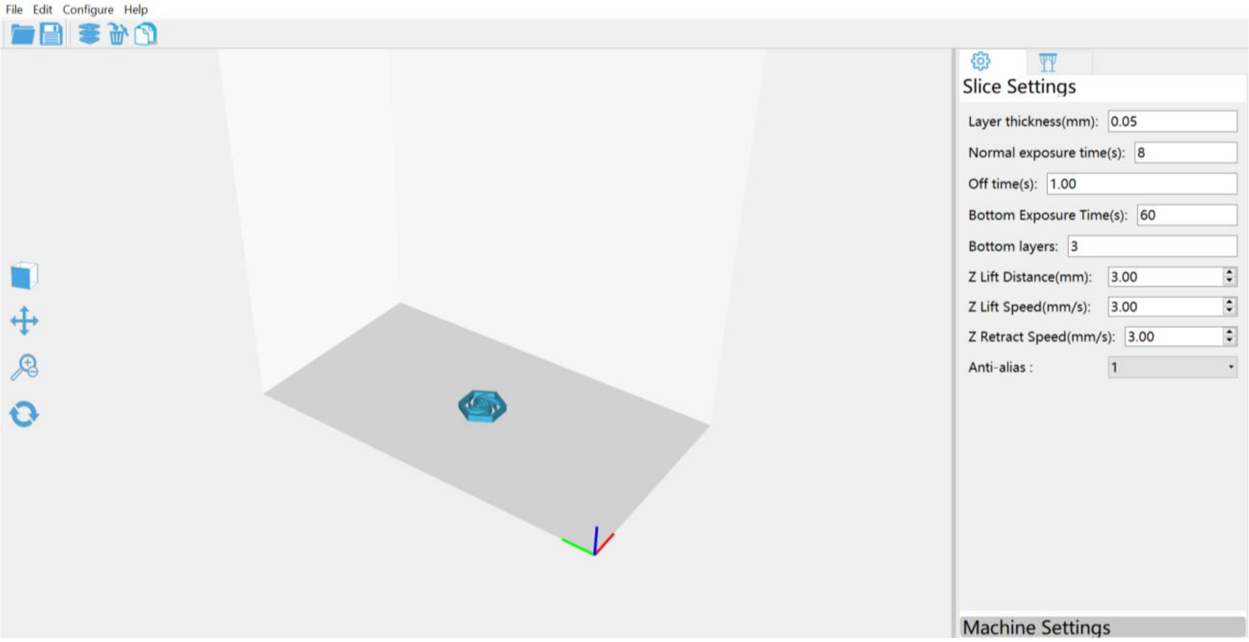


Figure 19: Photo of the results from the base exposure time tests for the clear plant-based Anycubic resin. The 20 second sample did not stick to the plate and is therefore not pictured. The 40, 60, and 80 second sample are pictured from left to right.

Figure 20: Photo of the results from the layer exposure time tests for the clear plant-based Anycubic resin. The 2 second sample did not stick to the build plate and is not pictured. The 6, 10, 14, and 18 second samples are shown from left to right.

Appendix B: 3D Printing Software Files



Slice Settings

Layer thickness(mm): 0.05
Normal exposure time(s): 8
Off time(s): 1.00
Bottom Exposure Time(s): 60
Bottom layers: 3
Z Lift Distance(mm): 3.00
Z Lift Speed(mm/s): 3.00
Z Retract Speed(mm/s): 3.00
Anti-alias : 1

Figure 21: Picture of the Photon slicing software used to create the 3D model that was then printed in each test. The default printer settings are shown on the right and were adjusted according to the test parameters. The specific hexagon shape shown here was used for each test, as it was small and therefore fast to print and showed significant detail in the center, which made analyzing and comparing each sample easier.

Appendix C: Raw Data and Observations

Anycubic Resin, provided	**Stuck to plate for print duration:**	**Not easy to remove:**	**Flash evident:**	**Object printed completely:**	**Detailed:**	**Defects:**	**Ideal Settings**
Base: 20							**Base: 50** **Layer: 8**
Base: 40	x						
Base: 60	x	x	x				
Base: 80	x	x	x				
Layer: 2							
Layer: 6				x	x	x	
Layer: 10				x			
Layer: 14				x			
Layer: 18				x			

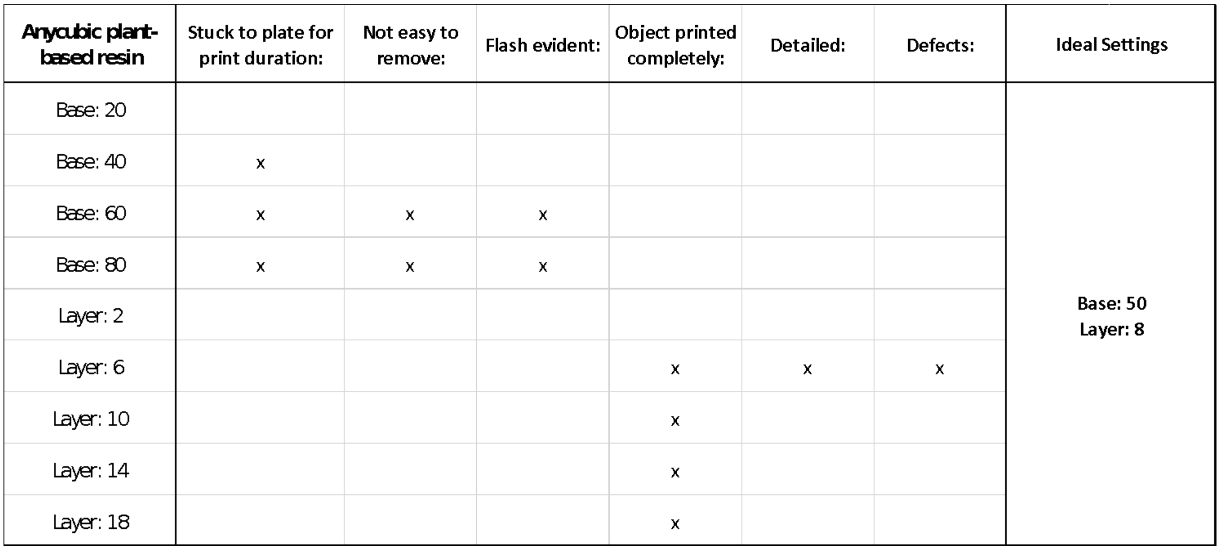
ELEGOO ABS-like resin	**Stuck to plate for print duration:**	**Not easy to remove:**	**Flash evident:**	**Object printed completely:**	**Detailed:**	**Defects:**	**Ideal Settings**
Base: 20							**Base: 60** **Layer: 10**
Base: 40							
Base: 60	x	x					
Base: 80	x	x	x				
Layer: 2							
Layer: 6							
Layer: 10				x	x		
Layer: 14				x	x		
Layer: 18				x			

ELEGOO Water-washing resin	**Stuck to plate for print duration:**	**Not easy to remove:**	**Flash evident:**	**Object printed completely:**	**Detailed:**	**Defects:**	**Ideal Settings**
Base: 20	x						**Base: 30** **Layer: 6**
Base: 40	x	x	x				
Base: 60	x	x	x				
Base: 80	x	x	x				
Layer: 2							
Layer: 6				x	x		
Layer: 10				x	x		
Layer: 14				x			
Layer: 18				x			

F69 Flexible TPU-like resin	**Stuck to plate for print duration:**	**Not easy to remove:**	**Flash evident:**	**Object printed completely:**	**Detailed:**	**Defects:**	**Ideal Settings**
Base: 20							**Base: 80** **Layer: 16**
Base: 40	x						
Base: 60	x						
Base: 80	x	x	x				
Layer: 2							
Layer: 6				x	x	x	
Layer: 10				x	x	x	
Layer: 14				x	x	x	
Layer: 18				x			

iFun Toughness resin	Stuck to plate for print duration:	Not easy to remove:	Flash evident:	Object printed completely:	Detailed:	Defects:	Ideal Settings
Base: 20							Base: 70 Layer: 12
Base: 40							
Base: 60	x						
Base: 80	x	x	x				
Layer: 2							
Layer: 6							
Layer: 10				x	x	x	
Layer: 14				x			
Layer: 18				x			

Wanhao flexible resin	Stuck to plate for print duration:	Not easy to remove:	Flash evident:	Object printed completely:	Detailed:	Defects:	Ideal Settings
Base: 20							Base: >80 Layer: 18
Base: 40							
Base: 60							
Base: 80	-						
Layer: 2							
Layer: 6							
Layer: 10							
Layer: 14				x	x	x	
Layer: 18				x	x		



Anycubic plant-based resin	**Stuck to plate for print duration:**	**Not easy to remove:**	**Flash evident:**	**Object printed completely:**	**Detailed:**	**Defects:**	**Ideal Settings**
Base: 20							**Base: 50** **Layer: 8**
Base: 40	x						
Base: 60	x	x	x				
Base: 80	x	x	x				
Layer: 2							
Layer: 6				x	x	x	
Layer: 10				x			
Layer: 14				x			
Layer: 18				x			

The above tables were used to take notes while resin testing. The first three columns were used during base exposure testing, and the subsequent three columns were used during layer exposure testing. If the print stuck to the plate for the duration of printing, the first column was marked. If significant force was needed to remove the print from the plate, the second column was marked. If a significant amount of extra material was cured on the build plate, the third column was marked. If the entire object was present, despite having defects, the fourth column was marked. If the object well resembled the 3D model, and well retained most of the detail, the fifth column was marked. If the object had significant defects, for example, separation in the cured layers, the sixth column was marked.