Minimization of the Warping Effect in Curing Formlabs Rigid 10K 3D Prints

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Resin 3D printing is used by researchers and engineers to expeditiously manufacture strong parts with complex shapes; however, defects can be introduced through the required curing process. Insufficiently supported or unevenly cured parts may become warped, reducing the viability of this high precision manufacturing option. This paper describes how to reduce deformation in a Formlabs Rigid 10K resin test print with cantilever beams of varying thicknesses from 2mm down to 1mm. Student members of Georgia Tech Experimental Rocketry (GTXR), a Ramblin' Rocket Club (RRC) project team at the Georgia Institute of Technology, conducted five separate tests, each with different curing processes. For all tests conducted, the time under ultraviolet light, the time under a certain temperature, the temperature itself, or the presence of water for the UV cure were varied. Curing Rigid 10K with UV light at room temperature followed by a heat cure at temperatures above or equal to 60°C for an extended period proved highly effective at reducing deformation for all beams. Placing the part underwater for the cure further reduced the warping to as low as 0.18mm. It is concluded that the optimal tested method to minimize deformation is a ten-minute underwater UV cure followed by a 75-minute heat cure at 60°C. By reducing warping, more complex parts may be 3D printed, such as external rocket shrouds and intricate tight-fit camera mounts. Additional research into curing other resins like Tough 2000 is being carried out to continue investigating the benefits of warp minimization in resin 3D printing for applications in two-stage spaceshot rockets and more complex vehicles.

I. Nomenclature

b	=	thickness of a beam [mm]
d	=	displacement [mm]
h_a	=	attached side height [mm]
h_d	=	deflected side height [mm]
T	=	non-ambient temperature [°C]
t_T	=	time spent curing at a non-ambient temperature [minutes]
t_U	=	time spent curing under ultraviolet light with ambient temperature [minutes]

II. Introduction

When engineering a system for use in aerospace applications, design is dependent on a myriad of factors, including structural compliance, durability, and manufacturability. Material choice plays a major role in all of these factors. Resin has become a popular material choice in industry-grade applications due to its structural properties. These can be tailored for resistance to external factors, such as heat, and the relative ease of using 3D additive manufacturing techniques to generate parts with complex, organic geometries. As a result, resin stands out as a viable material for the diversification of material properties it adds to an engineer's arsenal, as well as its maximal utility for parts with various purposes.

Resin is a Type 1 photopolymer, meaning that it hardens under exposure to light. Type 1 photopolymers are made of a series of monomers or oligomers that can undergo radical, cationic, or anionic chain polymerization under exposure to light. This creates cross-linked polymer networks, changing its mechanical and chemical properties [1]. The unique nature of this material has encouraged popular utilization in 3D manufacturing processes, like stereolithography (SLA) printing. In SLA printing, an ultraviolet light illuminates a layer of uncured resin in liquid form based on the

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cross-section of the part to harden it onto a base plate. The printer continues to cure the resin layer-by-layer, until the full part has been printed; however, even after the part is done printing, it remains only partially cured and must undergo a post-cure treatment that forms more cross-links, further hardening the print and reaching its optimal properties [2]. Modifying the makeup of the resin, as well as the method of polymerization, allows for variation in these post-cured properties.

A major drawback of resin 3D printing is the warping associated with the post-cure process. This occurs as a result of unevenly cured sections within the part or lack of support to overhanging structures. This effect is detrimental to applications that require accurate geometries, such as the cross section of a fin. An example of this is the fins on *Fire on High*, GTXR's 2023-2024 rocket. *Fire on High* flew with fins made of a Rigid 10K core fins with carbon fiber layups [3]. The core of the fins had noticeable deformation towards the leading edge, where the taper creates a thin region that approaches zero thickness. *Fire on High* experienced a phenomenon known as pitch-yaw roll coupling, leading to an in-flight failure of the vehicle. Since this was caused by the asymmetry of the fins, the issue of warped resin prints became paramount to solve.

Choosing Formlab's Rigid 10K as the resin to investigate for this study was primarily due to its potential as a fin core material for GTXR's 2024-2025 rocket, *Live and Let Fly*. The resin also has widespread use in many of GTXR's other rockets for various purposes, which bolstered the authors' decision to focus on this specific resin. Post-cured Rigid 10K has a tensile modulus range of 1460-1480ksi and a ultimate tensile strength ranging from 7710-9460psi [4]. The resin is brittle, with an elongation of 1% at fracture. Furthermore, it has moderate heat deflection of 218°C at 0.45 MPa. Through past experience, it was concluded that warping becomes a more prominent issue at smaller thicknesses. Therefore, a test part was designed to reflect the differing deformation effects acting on the slim beam thicknesses. Since warping is caused primarily during the post-curing process, the test parts were cured with five different cure settings to observe how factors like temperature, exposure to UV light, and the presence of water affect deformation in the finished part. Underwater curing was chosen as a post-curing method after preliminary research suggested it could reduce warping, since water can more effectively diffract UV light throughout the part, ideally leading to a more even cure. Furthermore, submerging the part in water reduces the part's exposure to oxygen, inhibiting the polymerization process. Previous research has found that underwater curing increases the flexural modulus of the resin, which could also minimize warping effects [5]. Additional cure setting variables, such as temperature and length of cure were decided based on Formlab's recommendations for curing Rigid 10K [6]. The test piece was designed to test multiple thicknesses at once by creating shapes resembling shelves of resin, which acted as cantilever beams. Several iterations of the design for the test piece were used to reduce the volume of resin used per print. As further testing was conducted, it was found that thicker shelves did not need be tested due to minimal warping after initial tests of post-cure processing procedures.

III. Experimental Setup

The deformation of 3D printed resin parts was analyzed with respect to varying thickness and cure methods. This required the design of a test print that satisfied all experimental conditions, as well as being manufacturable and able to sustain the post curing process. The experiments were derived so that the end result would provide insight into optimal practices for the minimization of resin warping.

A. Design

In order to understand how various cure methods impacted the deformation of prints of various thicknesses, a test print was designed so that each thickness could be tested at once for each cure setting. All iterations of the test piece included a thick base and wall for support, with flat cantilever beams of varying thicknesses jutting out from the wall. Initially, 11 beams, or shelves, were created to test thicknesses from 1.0 mm to 2.0 mm with a step size of 0.1 mm. To allow ample space for vertical deformation while keeping the print relatively short, two columns of alternating shelves were created. The SOLIDWORKS sketch included the base, wall, and 11 beams, each with their respective thicknesses, 1.0 mm being the top shelf and 2.0 mm being the bottom shelf. The space between the bottom of an upper shelf and the top of a lower shelf was 5mm. This design was used for cure methods D, E, and F, and is shown in Figure 1; however, it was substituted for a smaller test print with fewer shelves in order to focus on thicknesses ranging from 1.0 mm to 1.5 mm, with a step size of 0.1 mm. The new test piece had the same structure, but with decreased spacing of 8.0 mm between each shelf of the same column. This test piece was used for cure methods G and U, and is shown in Figure 2. The reason for reducing the sizing was to minimize the amount of resin used for each test, and did not affect the study since thicknesses greater than 1.5 mm were already very low. In both test pieces, the shelves were 54.3 mm long and 25 mm wide.

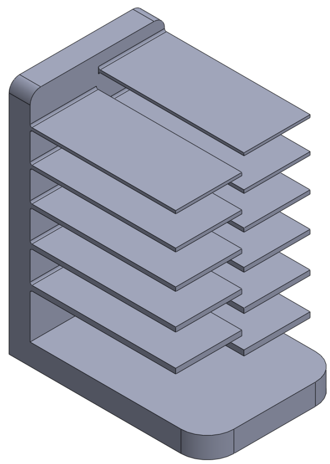


Fig. 1 Original test print CAD

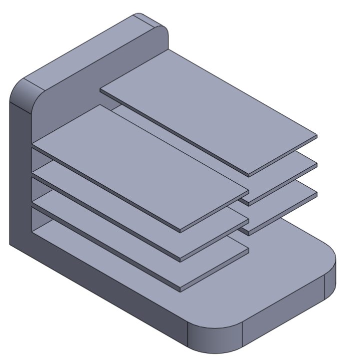


Fig. 2 Iterated version of test print CAD with fewer shelves and truncated height

B. Manufacturing

The manufacturing of the test piece involved converting the SOLIDWORKS .SLDPRT file into a .STL file so that it could be imported into a slicer. For these 3D prints, Formlabs's PreForm application was used. In PreForm, the resin type and printer version were chosen. Then, the part was uploaded into the workspace to be oriented as needed. Supports were auto-generated; however, supports on the shelves themselves were manually removed as much as possible to minimize their influence on the observed deformation. A vertical orientation with slight tilt such that the base and wall form a 'V' shape was most often used as an optimal printing orientation.

The printers used in this study included Formlabs's Form 3, Form 4, and Form 4L SLA printers, depending on which ones were available during testing periods. Figure 3 shows the original 3D printed test structure.

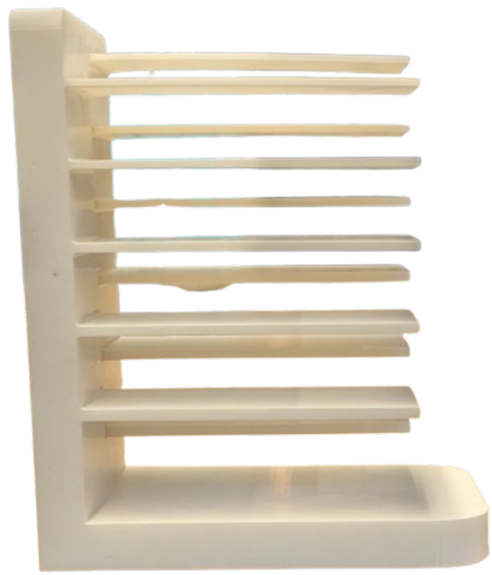


Fig. 3 3D printed test print with visible warping

C. Post-Processing

The key to minimizing warping lies in the post-processing method of curing. This process is carried out in a professional-grade curing instrument, such as the Form Cure L V2, and it consists of a combination of ultraviolet light exposure and a curated temperature surrounding and penetrating the part. While the first variable triggers the polymerization process, the latter influences the rate of curing and the final quality of the resin. To finalize planning for the curing procedure, analysis on industry-wide curing standards was conducted. Formlabs finds a Rigid 10K cure of 70° C for 60 minutes optimal for most purposes, also emphasizing that the various post-curing options presented can be advantageous for different applications [6]. Additionally, most processes only consist of one step, condensing the UV and heat cures into a single curing procedure; however, separating these steps can lead to less warping and allow the part to reach a state with durable material properties. For Rigid 10K, this translates to the stiffness of the resin print.

Thus, the curing process was conducted in two steps for this experiment. The first step under ultraviolet light was carried out at room temperature to minimize the heating effects on the deformation of the part. The duration of this step varied between 10 to 30 minutes across tests. The second step focused on finalizing the polymerization process through external heating, which was concurrent to the ultraviolet light exposure. This operation was carried out at a uniform temperature for each test, having an overall testing range encompassing values from 60 to 80°C.

Five curing methods were designed. Method D consisted of curing the resin print for 30 minutes under ultraviolet light at ambient temperature and then for 30 minutes under an additional increased temperature of 80°C. Method E comprised of curing the resin print for 15 minutes under ultraviolet light at ambient temperature and then for 45 minutes under a temperature of 75°C. Method F involved curing the resin print for 10 minutes under ultraviolet light at ambient temperature and then for 60 minutes under a temperature of 70°C. Method G consisted of curing the resin print for 10 minutes under ultraviolet light at ambient temperature and then for 75 minutes under a temperature of 60°C. Lastly, Method U is identical to G apart from the additional constraint of completing the process fully submerged in water.

Methods D, E and F were carried out for beams thicknesses varying from 1 to 2mm; however, methods G and U were only tested for beam thicknesses between 1 and 1.5mm. The decision to alter the test print better allowed the goal of the research to be achieved, minimizing warping at the smallest achievable scale of resin printing.

Table 1 Experimental Cure Methods

Method	D	E	F	G	U
t_U	30 min	15 min	10 min	10 min	10 min
t_T	30 min	45 min	60 min	75 min	75 min
T	80°C	75°C	70°C	60°C	60°C
Underwater	No	No	No	No	Yes

IV. Data Collection

Data was collected through caliper measurements of beam to base distances, comparing these to the distance of the end of the beam to the base. Two measurements were carried out per beam on two separate edges: the edge on the deflected side and the edge on the attached side. The total deformation for each shelf thickness was calculated using Equation 1. Tables 2 through 6 display the measurements taken for each print, as well as the calculated displacement.

$$d = h_a - h_d \tag{1}$$

Accuracy presented as an issue in initial phases of the experiment. If too much pressure was applied on a beam, it would stray from its position at rest, skewing results. Therefore, differing pressures had to be tested for each beam to check the accuracy of a measurement without over- or under-pressurizing the beam in question. Multiple different procedures were conducted to find the pressure required for maximal precision in the measurements. The deformation was measured 3 times for each thickness, then averaged out.

Table 2 Displacement for Cure Setting D

Attached Side Height (mm)	Deflected Side Height (mm)	Thickness (mm)	Displacement (mm)
84.84	82.68	1.00	1.73
78.74	77.55	1.10	1.45
72.67	71.68	1.20	0.99
66.60	65.79	1.30	0.84
60.10	59.59	1.40	0.51
53.72	52.86	1.5	0.61
47.09	46.79	1.6	0.30
40.64	40.21	1.7	0.43
33.78	33.60	1.8	0.36
27.18	26.70	1.90	0.46
20.32	19.91	2.00	0.46

Table 3 Displacement for Cure Setting E

Attached Side Height (mm)	Deflected Side Height (mm)	Thickness (mm)	Displacement (mm)
84.84	82.96	1	1.88
78.79	77.57	1.10	1.22
72.64	71.53	1.20	1.12
66.78	65.63	1.30	1.14
60.30	59.69	1.40	0.61
53.85	52.91	1.50	0.79
47.04	46.74	1.60	0.64
40.69	40.23	1.70	0.46
34.42	34.14	1.80	0.28
27.00	26.82	1.90	0.18
20.40	20.30	2.00	0.1

Table 4 Displacement for Cure Setting F

Attached Side Height (mm)	Deflected Side Height (mm)	Thickness (mm)	Displacement (mm)
84.89	83.36	1.00	1.52
79.15	78.03	1.10	1.12
72.71	71.78	1.20	0.93
66.42	65.56	1.30	0.86
60.17	59.64	1.40	0.53
53.57	53.04	1.50	0.53
47.63	47.19	1.60	0.43
40.18	39.88	1.70	0.30
33.91	33.76	1.80	0.15
26.95	26.85	1.90	0.10
19.99	19.96	2.00	0.03

Table 5 Displacement for Cure Setting G

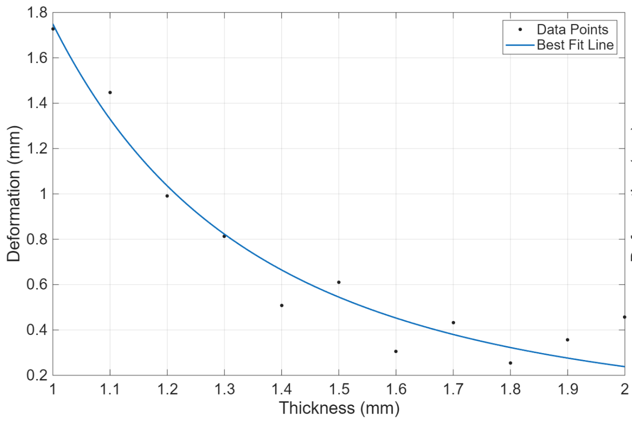
Attached Side Height (mm)	Deflected Side Height (mm)	Thickness (mm)	Displacement (mm)
41.40	40.46	1.00	0.94
35.86	35.06	1.10	0.80
32.03	31.34	1.20	0.69
26.97	26.34	1.30	0.64
22.77	22.30	1.40	0.47
17.50	17.36	1.50	0.14

Table 6 Displacement for Cure Setting U

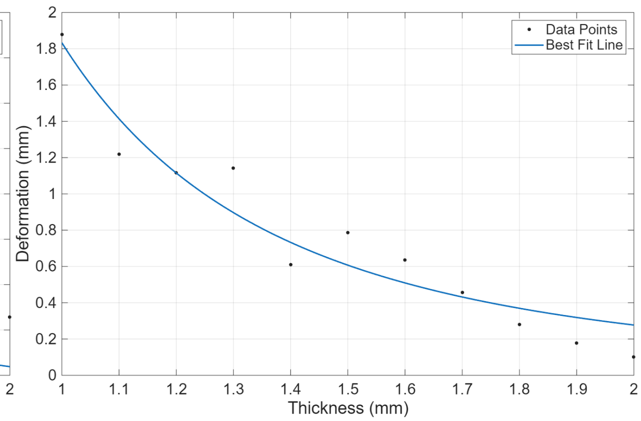
Attached Side Height (mm)	Deflected Side Height (mm)	Thickness (mm)	Displacement (mm)
41.12	40.94	1.00	0.18
35.94	35.73	1.10	0.22
31.98	31.80	1.20	0.18
27.03	26.85	1.30	0.18
22.76	22.64	1.40	0.11
17.55	17.46	1.50	0.09

V. Results

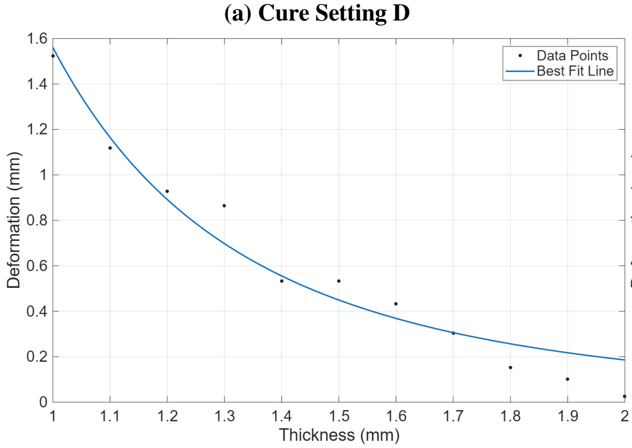
The deformation data was plotted as a function of resin thickness for each cure method case. A power fit was then applied to the data to create a curve of best fit. Figure 4 details the plotted results for each of the cure settings, showing the individual data points as well as the power fit curve.



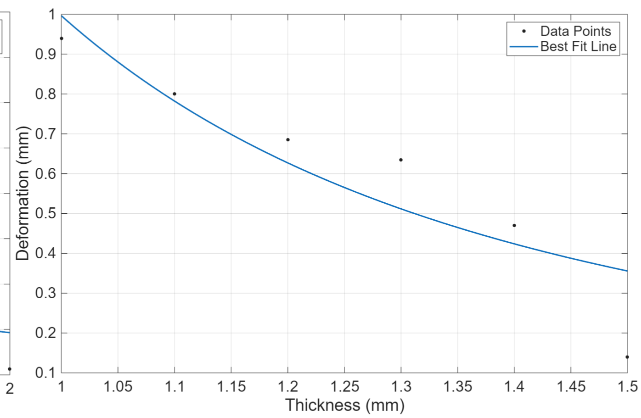
(a) Cure Setting D



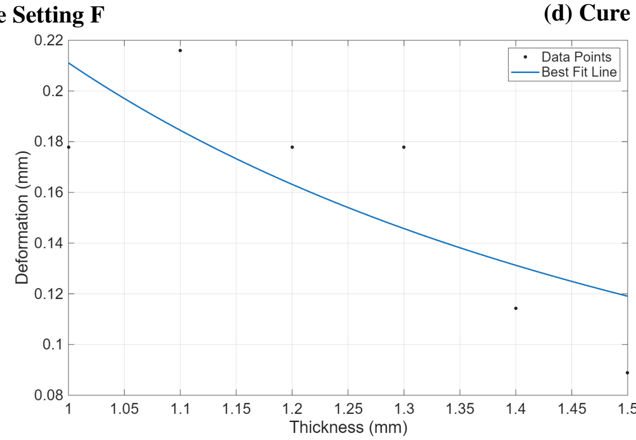
(b) Cure Setting E



(c) Cure Setting F



(d) Cure Setting G



(e) Cure Setting U

Fig. 4 Deformation as a function of thickness for each individual cure method

In Figures 5 and 6, the individual data points are neglected to focus on the overall trends in deformation.

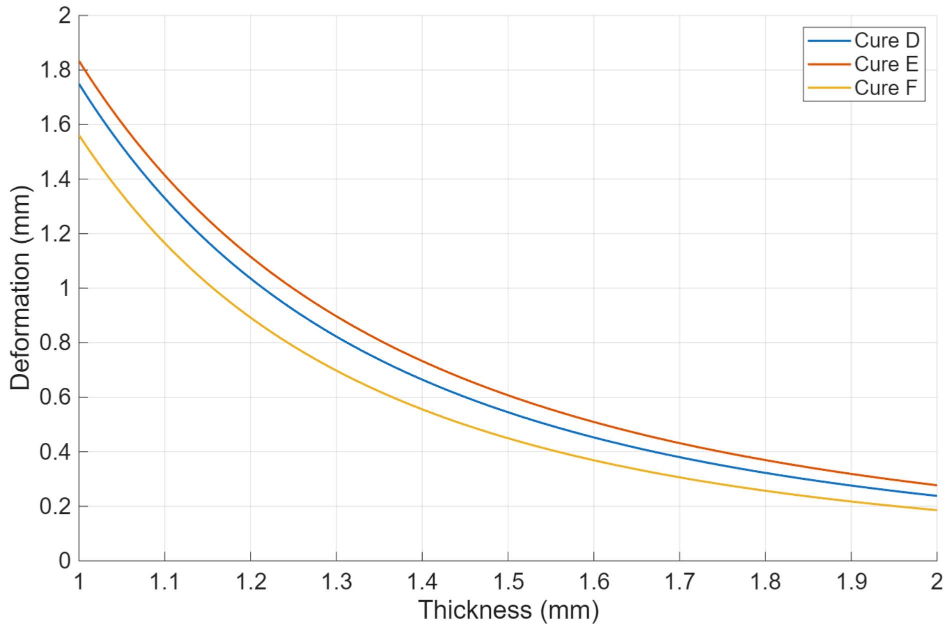


Fig. 5 Deflection per thickness - methods D, E and F, using first iteration of test print

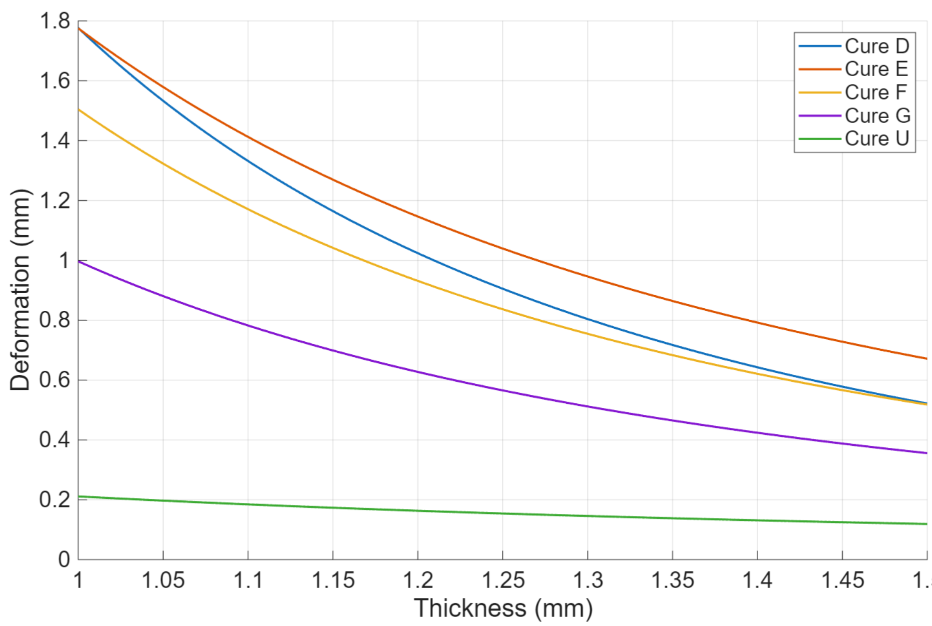


Fig. 6 Deflection per thickness - all methods

VI. Discussion

Figure 4 shows the data points from each cure method as well as a best fit curve. The plots clearly demonstrate that as thickness increases, the resulting deformation of the resin print decreases. As the thickness decreases, the resulting deformation increases substantially in a non-linear manner. As such, a power fit was chosen to represent the data points. This fit best captures the steep increase in deformation with a decrease in thickness. Two reasons can be given to justify this decision, as opposed to choosing a polynomial fit. First, the power fit more often than not posed a higher R^2 value, indicating a closer fit. Second, a power fit allows for a greater degree of flexibility by fitting to a range of polynomial orders. With this curve-fitted data, it can be concluded that as the thickness of the beams increase, deformation decreases exponentially.

Figure 5 simply plots the curve of best fit relating the deformation to beam thicknesses for cure methods D, E, and F. The thickness range is due to the fact that cure methods D, E, and F were tested using the first iteration of the test print design. From the figure, it is deduced that Cure F has the lowest deformation for all thicknesses when compared to cure methods D and E. The maximum deformation value observed was 1.88 mm for Method E at the thinnest beam and the minimum value achieved for the same beam thickness was 1.52 mm through Method F.

Figure 6 displays the deflection as a function of thickness, just as Figure 5, and has the same relationships. However, it ranges from thicknesses between 1 and 1.5 mm only and additionally includes methods G and U. Cure U has the lowest warping effects for all cantilever beams. The maximum deflection value observed is, again, 1.88 mm for the first beam, which resulted from curing with Method E. The minimum value of deformation for the same beam is 0.18 mm and was achieved by cure U. Cure U has deflection values that decrease by increasing beam thickness; however, the rate of the decrease is much lower than for the other curves. For both Figure 5 and 6, Cure E has the highest deformation for all beams.

Cure F includes the method recommended by Formlabs, which consists of curing for 60 minutes at 70°C with an added UV step beforehand. Comparing procedures D and E to F in Figure 1 shows the latter has the leading results. However, comparing techniques G and U to F in Figure 2 reveals optimizing Formlab's curing method is feasible, as the deflection for all beams undergoing processes G and U was lower than for F. The altered parameters between G and F consist of 66% shorter UV exposure and 25% longer exposure to 14% lower heating. Although the beams still experienced reduced deformation, there was a considerable decrease of deformation by a factor of 1.5. Warping was therefore minimized when temperature was lowered and the exposure was prolonged. Increasing exposure was found to decrease deflection as it increased the time the resin had to form cross-links. This exploration doesn't cover the reason lowering the temperature reduced deformation; however, the authors theorize that increasing the temperature lowers the structural rigidity of the resin, which could lead to increased warping.

Cure U has the optimal curve, minimizing warping compared to cure F. When compared to cure G, deformation considerably decreased as well, yet the singular difference between cure G and U was that U was processed underwater. By submerging the print underwater during the UV cure, light is scattered throughout the resin print more effectively and evenly. This reduces areas of uncured resin, which introduces internal forces that cause warping. Additionally, underwater curing minimizes exposure to oxygen gas, which inhibits the curing process. Therefore, a more thorough and timely cure may be conducted. This analysis confirms underwater curing improves print accuracy, minimizing deflection for all thicknesses.

VII. Conclusion

The post-curing process of a 3D printed resin part is essential in achieving optimal quality, shape and resin properties. Although 3D printed resin parts experience at least reduced warping in the post-curing process,this paper demonstrates the ability to minimize this effect. To further this research, an exploration into how other resins deform during the cure process and optimal cure settings for each will be carried out. Additionally, tests will be conducted to understand the effect of these cure methods on the material properties of the resin, including Young's Modulus, and heat deflection temperature. These studies will provide a deeper understanding of resin's material properties and on how the curing process affects the performance of resin 3D printed parts. Ultimately, organizations, such as Georgia Tech Experimental Rocketry, will be able to utilize this knowledge to make informed decisions regarding the design and manufacturing of complex systems.

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