FORMLABS WHITE PAPER:

How Mechanical Properties of Stereolithography 3D Prints are Affected by UV Curing

By Zachary Zguris, PhD

formlabs.com

ABSTRACT

The post-cure of parts printed with Formlabs resins on the Form 1+ and Form 2 printers was thoroughly investigated. From the results, we are now able to recommend post-cure procedures for Castable, Standard, and Tough Resins that provide the highest mechanical properties. In all cases, a 405 nm light source during post-cure is superior to an equivalent level of lower wavelength light, such as 365 nm. Counter to the common belief that more light results in better post-cured properties, the optimum flux on a printed part needed to obtain maximum mechanical properties during post-cure has been determined to be 1.25 mW/cm^2. It was found that post-curing at higher temperatures results in a shorter time to full cure. Additionally, higher temperatures lead to higher mechanical properties. A complete list of recommended post-cure times and temperatures for all of Formlabs resins is provided.

INTRODUCTION

Prior to this work, there had been little scientific study about post-curing prints made on Formlabs desktop SLA 3D printers. The Formlabs line of SLA resins includes a series of Standard Resins: Clear, White, Grey, and Black. In addition to the Standard Resin family, Formlabs offers Functional Resins: Tough, Castable, and Flexible. Each resin is a finely-tuned proprietary formulation developed and engineered from the ground up to work with the Form 1, Form 1+ and Form 2 SLA 3D printers. These machines all use a 405 nm laser. All of the Formlabs resins are tailored to this wavelength.

Other manufacturers of SLA 3D printing resins design their products for use with differing wavelengths, chemistries, and print processes. Recommended post-cure procedures for other brands of 3D printing resins are not likely to work with Formlabs resins for best results. To date, Formlabs' recommendation for print post-curing is based on generally accepted post-cure practices in the industry.

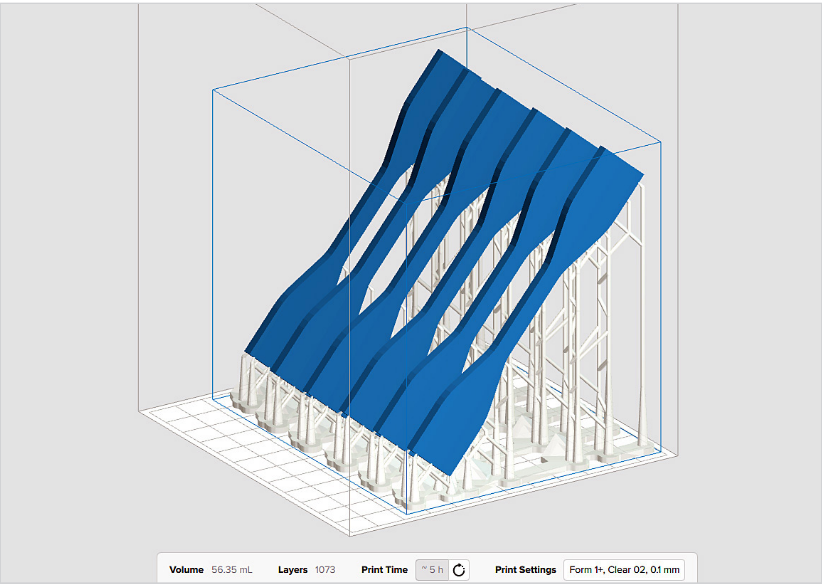
After realizing that Formlabs resins are each a unique formulation engineered to work specifically with our printers, we set out to study the post-cure process in detail with the singular goal of developing the best possible post-cure procedures for our users. To this end, the effects of the post-cure process parameters of temperature, wavelength, time, and radiant flux on the mechanical properties of prints made using Formlabs printers and resins were studied.

EXPERIMENTAL

Experiments were designed to determine the effect of the individual post-cure process parameters of temperature, wavelength, time, and flux. The experimental setups were designed to eliminate all controllable variables outside of the specific one being studied in each set of experiments.

All of the mechanical data was acquired with a Test Resources Universal Testing Machine (Model 500LB Actuator, Model SM-500-294 Load Cell, Epsilon Technology Corp. Axial Extensometer Model 3542-0100-050-ST). ASTM D638 type IV tensile bars were used as the standard printed part throughout this research. In all plots, the error bars report standard deviation for the mean of four samples.

Both Form 1+ and Form 2 printed ASTM D638 type IV tensile bars were used for experimental samples. All of the data presented, unless otherwise indicated, is for samples printed using Formlabs Clear V2 Resin at a 100-µm layer height. The samples were manually oriented at 45 degrees in the x direction and 0 degrees in the y direction. Supports were carefully edited in PreForm software to eliminate any defects in the necked region caused by support touch points. The orientation used to print tensile bars is illustrated in Figure 1.



Volume 56.35 mL **Layers** 1073 **Print Time** ~ 5 h **Print Settings** Form 1+, Clear 02, 0.1 mm

Figure 1: PreForm Orientation of ASTM Type IV Tensile Bars

Time, temperature, and wavelength experiments were all performed on the same experimental apparatus, shown in Figure 2. This cure study apparatus (CSA) is composed of a heat sink with a mounted 10W LED array supported a fixed distance over tensile bar samples located in a transparent acrylic holder over a reflective aluminum surface. A fan blows continuously over the samples to maintain a constant uniform sample temperature. The CSA frame is an open structure to facilitate air movement over samples. The CSA frame locates the LED array in a central position a fixed distance of 90 mm over the samples. An acrylic sample holder positions each of four tensile samples to eliminate positional variation. The uniformity of the light over the sample holder was verified. No variations in mechanical properties due to sample location were found. Additional equipment used consisted of a four-channel Type K thermocouple data logger (Measurement Computing model USB-TC) and an Auber-WS PID temperature controlled CADCO XAF013 Oven.

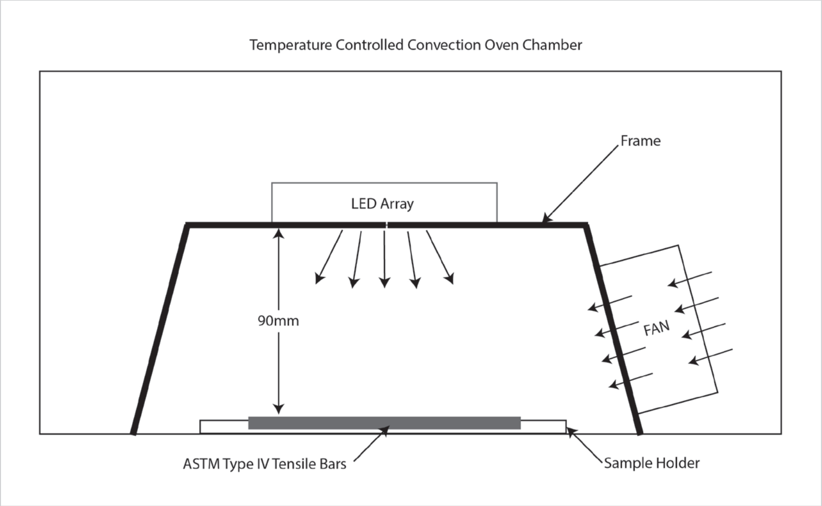


Figure 2: Cure Study Apparatus

Flux experiments at 405 nm were carried out in a separate test cure chamber (TCC) built specifically for further post-cure research and study. The TCC was built to allow control of the amount of 405 nm light the test samples were exposed to during post-cure. This second apparatus consists of an insulated chamber with multiple light sources, a convection heater, temperature control, time control, and a locating sample holder as shown in Figure 3. The TCC allowed for the control of one to four 10W LED arrays in addition to a 3.2W star puck LED. This apparatus was used to determine the effects that differing levels of radiant power incident on a post-curing part's surface had on mechanical properties.

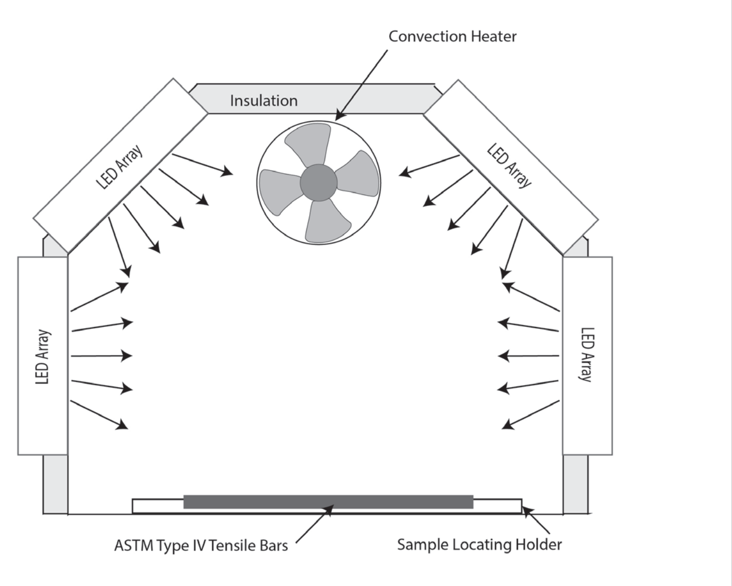


Figure 3: Post-Cure Chamber Used for Radiant Flux Experiments

Light sources consisted of 10W LED arrays from Shenzhen Yonton Opto Company with the three different output wavelengths of 365 nm, 385 nm, and 405 nm. Because it was not readily possible to control the luminous power of each array, the input power into the LED array was fixed and held constant by a commercial LED driver (Shenzhen Yonton Opto Co. model: 10W[3x3]). Each LED array was powered by the same 10W constant current DC power source. All of these components were from a single source supplier. Each chip was identical in form factor and input power. In addition to the three LED arrays, a 9W 365 nm UV Fluorescent bulb (UV-9W 365 nm) was also investigated. A Thorlabs UV-Vis spectrometer (model: CCS100) was used to quantify the wavelength produced by each light source. A Thorlabs Digital Handheld Optical Power and Energy Meter Console (model: PM100D) with 5 mm dia integrating sphere (model: S140C) was used to quantify the flux.

TABLE 1: MEASURED OUTPUT OF LIGHT SOURCES

Array Wavelength (nm)	Peak Wavelength (nm)	Power (mW)
405	406.9	3.41
385	389.2	1.61
365	368.1	1.17
Fluorescent 365	366	0.923

The evaluation of the light sources is summarized in Table 1. Results verify that each light source produces light near enough to the specified wavelength but to differing efficiencies for the same input power of 10W. Figures 4 through Figure 7 show the spectra for each light source. The LED arrays produce similar peaks around but slightly above the reported nominal value of the array. The 9W UV fluorescent bulb shows a broader peak around 365 nm in addition to the expected Mercury spectrum overlay.

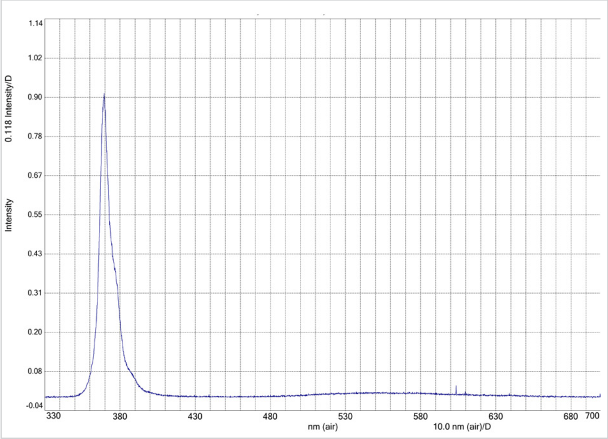


Figure 4: Spectrum of 365 nm 10W LED Array

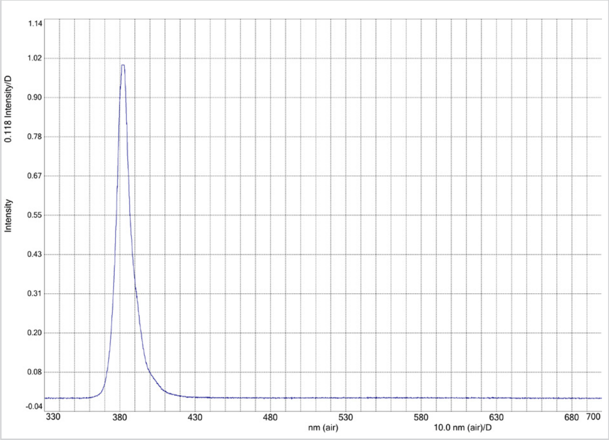


Figure 5: Spectrum of 385 nm 10W LED Array

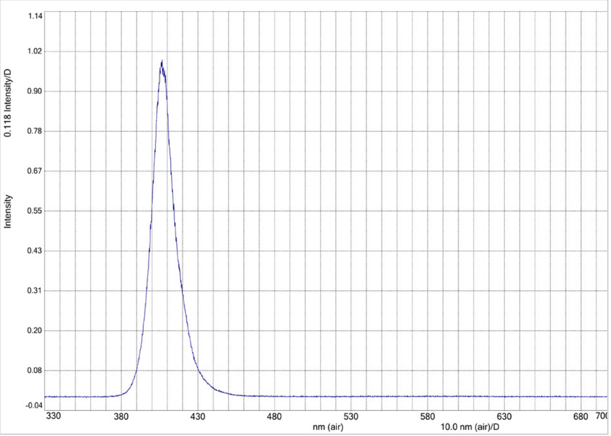


Figure 6: Spectrum of 405 nm 10W LED Array

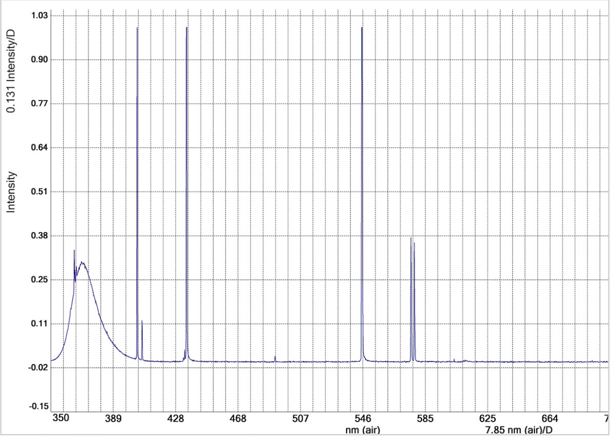


Figure 7: Spectrum of 365 nm 9W Fluorescent Bulb

RESULTS AND DISCUSSION:

Our study of the effects of three wavelengths, 365 nm, 385 nm, and 405 nm, on the post-cured mechanical properties of printed parts showed a distinct difference. The results of these experiments are shown in Figures 8 and 9.

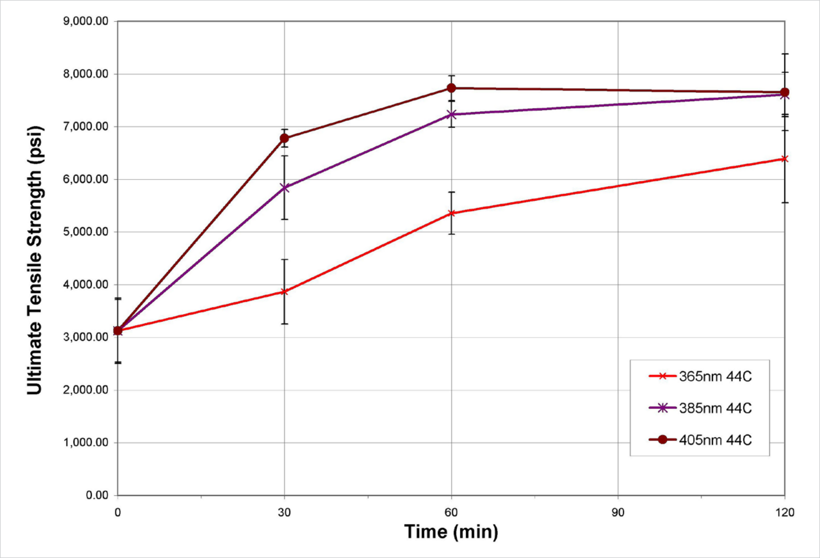


Figure 8: Effect of Clear V2 Post-Cure Wavelength on Ultimate Tensile Strength

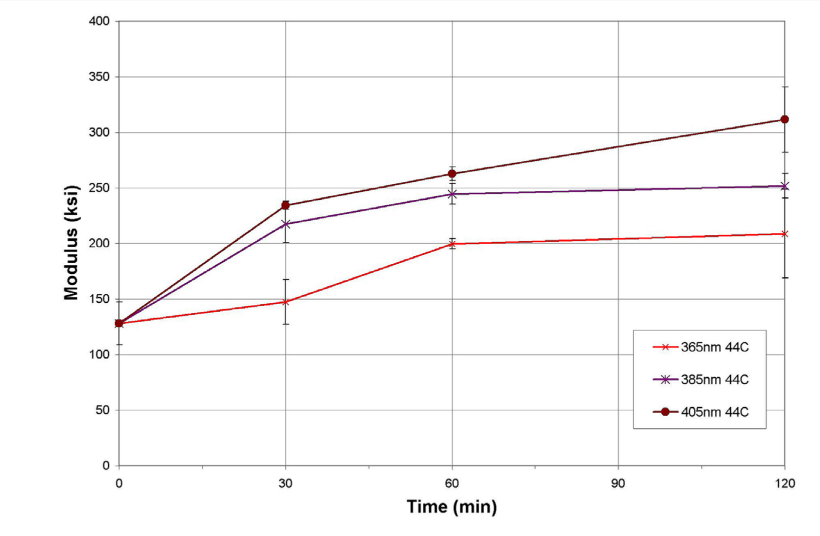


Figure 9: Effect of Clear V2 Post-Cure Wavelength on Modulus

We find that the best modulus and tensile strength are developed by post-curing with a 405 nm light source. With a post-cure of 120 minutes and 44 °C, the modulus at 365 nm is only 67% that of the 405 nm samples. There is a significant difference in the post-cured properties at each wavelength, especially so at shorter post-cure times. This is not surprising given that Formlabs resins are designed to work with the Form 1, Form 1+, and Form 2 printers, all of which use a 405 nm laser. While 365 nm and 385 nm light both produce post-cured modulus and tensile strengths that are higher than uncured "green" state samples shown at t=0, neither approach the properties obtained with a 405 nm source post-cure.

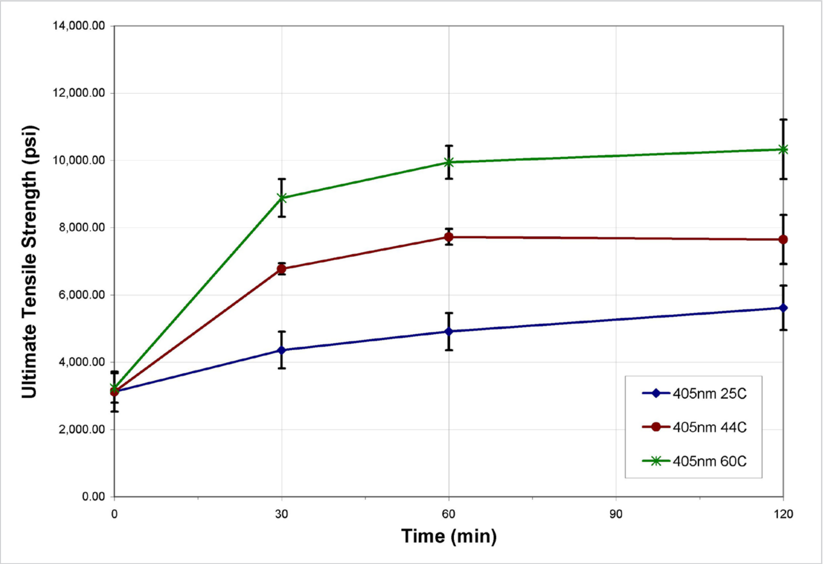


Figure 10: Effect of Clear V2 Post-Cure Temperature on Ultimate Tensile Strength

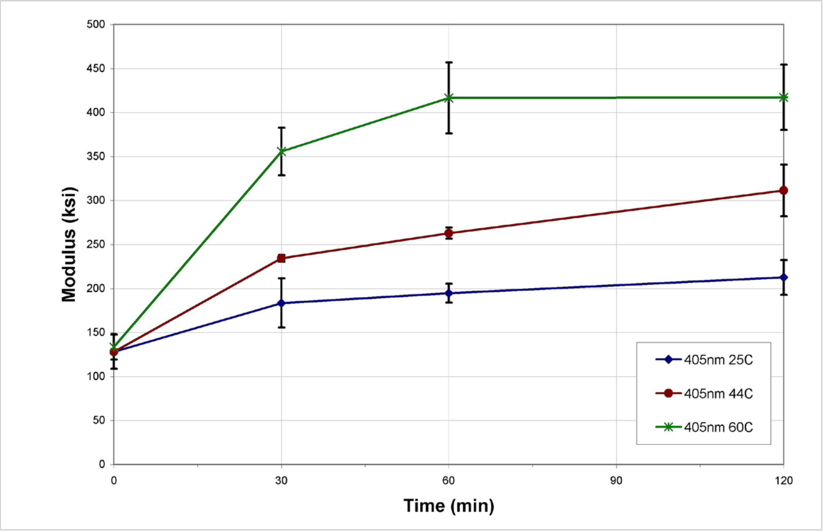


Figure 11: Effect of Clear V2 Post-Cure Temperature on Modulus

The effect of temperature on the post-cured modulus and ultimate tensile strength of printed Formlabs Clear V2 Resin are presented in Figures 10 and 11 respectively. With increasing post-cure temperature, there is a shorter time to achieve a fully post-cured state in which the material has reached the maximum mechanical properties possible at that temperature. In addition to an increased cure rate, the maximum obtainable modulus and tensile strength increase with temperature. A higher post-cure temperature not only yields a fully cured state more quickly, but it also yields a fully cured state with higher mechanical properties.

RADIANT POWER

Investigating the effect the amount of light has on the post-cured mechanical properties resulted in discovering that there is an optimum value of 405 nm flux that produces the best mechanical properties. Experiments were done post-curing samples at different radiant flux levels. Incident flux was quantified at each level of exposure using a 5 mm integrating sphere. The measured incident flux data is presented in Figure 12. This shows that there is a maximum value of modulus developed with an exposure in the range of approximately 1.25 mW/cm^2.

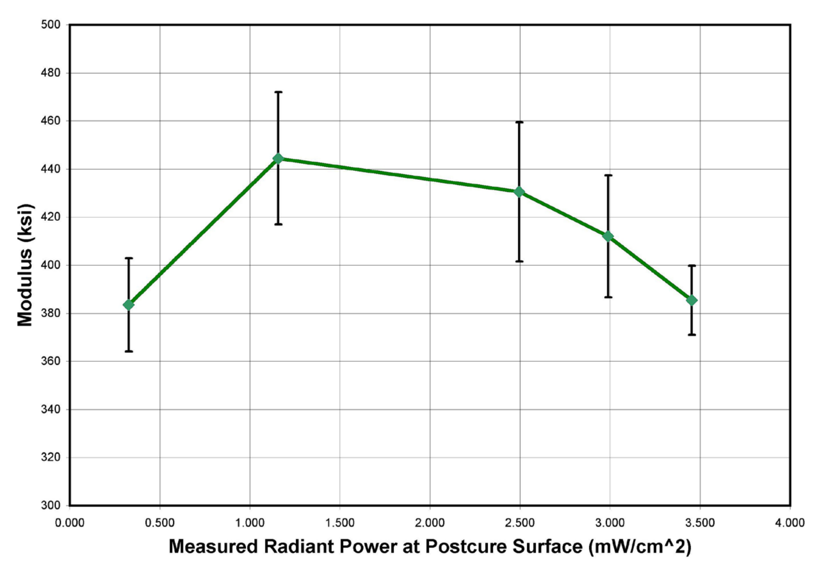


Figure 12: Measured 405 nm power vs Clear V2 Modulus (60 ºC for 60 min)

The effect of radiant power on the modulus of Clear V2 post-cured parts exposed to 405 nm light at 60 ºC for 60 min in a controlled geometry is shown as Figure 12. The optimum radiant power that produces the maximum modulus and tensile strength is 1.25 mW/cm^2. This is the flux generated by a single 10W LED array in the TCC. When radiant power decreases below this level, there is not enough light to post-cure well, and there is a decrease in mechanical properties. Using a higher flux also results in lesser mechanical properties. This is counterintuitive to the common assumption that more light will post-cure parts better.

Fundamentally, this can be explained by the competing radical reactions of initiation, propagation, and termination. In addition, there is limited chain mobility of the crosslinked polymer network that plays a role[1]. A high flux will generate a large number of radicals. These are more likely to find each other and die rather than see an unreacted double bond in the network[2]. The results from investigating the temperature effects on post-curing imply that the mobility of unreacted double bonds is a limiting condition in overall conversion of double bonds. The propagating radical on the kinetic chain is limited spatially by the tethered backbone chain tying it into the crosslinked polymer network of the printed part[2]. This balance between initiation by radiant flux and kinetic chain mobility results in the maximum properties obtained that we see at approximately 1.25 mW/cm^2.

For exposure levels above and below this optimum value, there is a decrease in the modulus of the cured part. When designing a cure chamber, this value of 1.25 mW/cm^2 should be used to achieve the best possible post-cure properties.

TOUGH RESIN

Similar to Formlabs Standard Resins, post-curing of Formlabs Tough Resin is best achieved using heating and a 405 nm light source as shown in Figures 13 and 14. One thing to note is that Tough has a heat deflection temperature of approximately 43 °C at 66 psi. In post-curing at elevated temperatures, staying at or below this temperature will minimize distortion and warping of the 3D printed part. Tough is completely post-cured in only 30 minutes at 44 °C, with longer post-cure time showing little further gains in properties with less than a 5% improvement in modulus with an additional 90 minutes. This shorter post-cure time is likely due to the more flexible polymer matrix that makes Tough Resin tougher than Standard Resins.

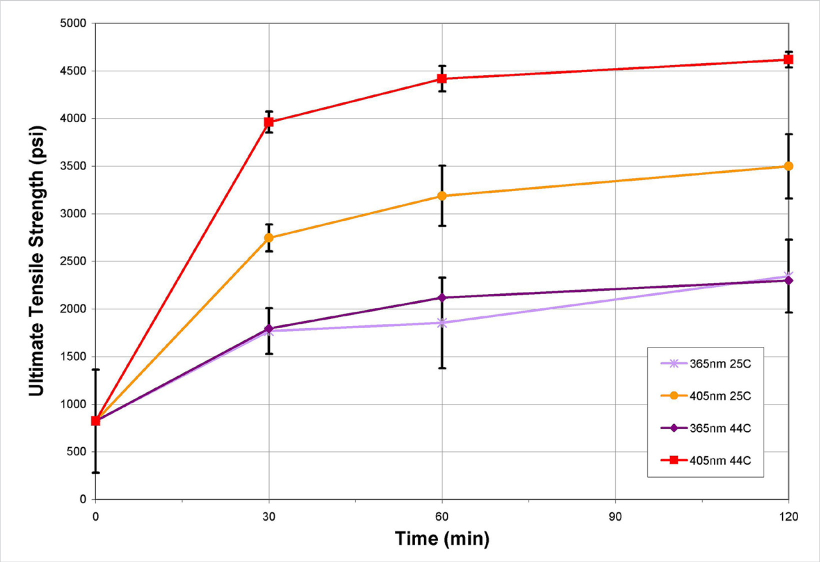


Figure 13: Post-Cured Tensile Strength of Tough

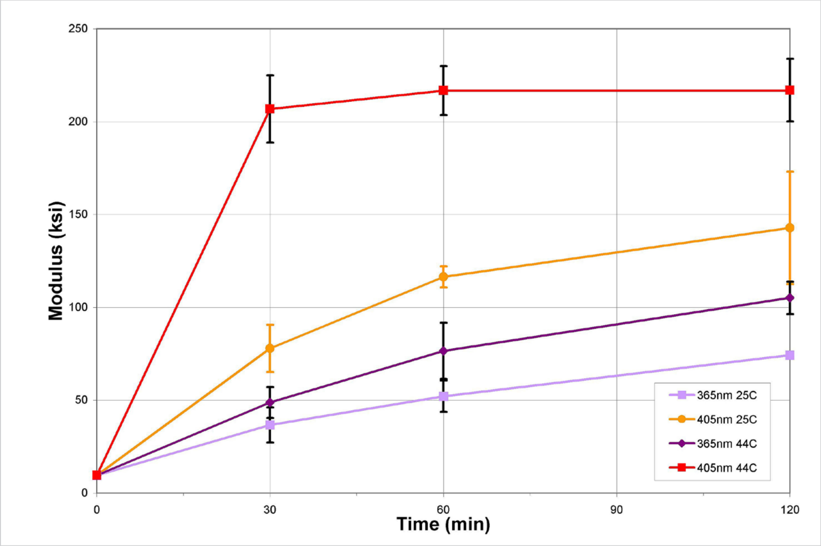


Figure 14: Post-Cured Modulus of Tough

CASTABLE RESIN

Post-cure of Castable Resin shows a rapid initial increase in mechanical properties, similar to Tough. Unlike Tough, it continues to cure beyond this first 30 minutes. There is a very large increase in post-cured properties over green mechanical properties. This order of magnitude increase in properties is a good reason to post-cure all Castable prints prior to using them in an investment casting process. Post-curing Castable Resin will yield better results in castings. The post-cured prints will be stronger and stiffer, and thus less likely to deform during mold making.

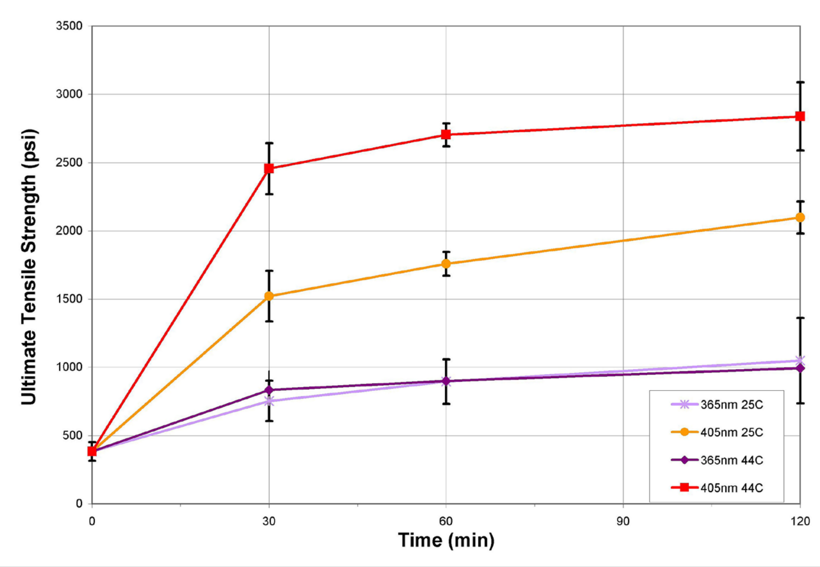


Figure 15: Post-Cured Tensile Strength of Castable

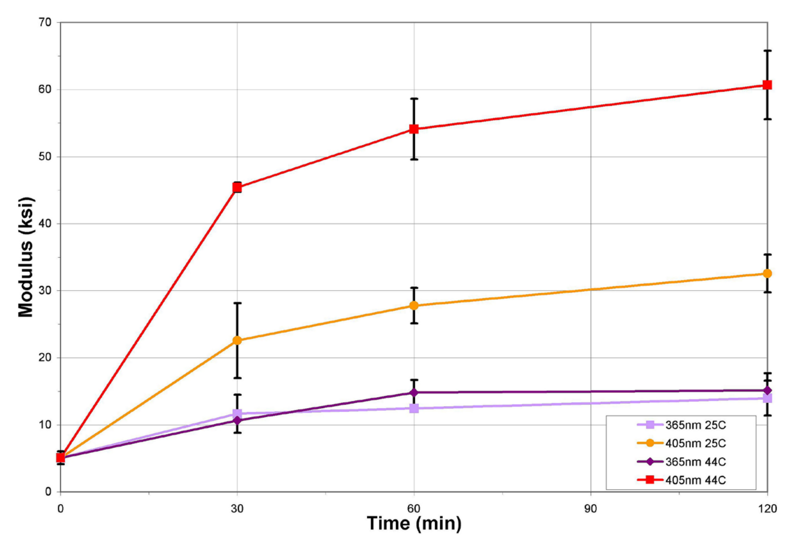


Figure 16: Post-Cured Modulus of Castable

NAIL SPA VS. HEATED 405 NM POST-CURE

A nail spa post-cures prints well. The nail spas recommended by Formlabs use 365 nm light produced by fluorescent bulbs that also effectively heat the chamber. The 365 nm light is absorbed well by the resin, which further heats parts as they are being post-cured. Experimentally, we have determined that maximum obtainable Clear V2 properties after 120 min exposure in the nail spa are 92% of those obtained curing for the same length of time using 405 nm at 60 °C in the TCC. One distinct difference in properties between these two procedures is the impact toughness, with nail-spa-cured parts having only 62% of the impact strength of 405 nm 60 °C post-cured samples. This shows that a nail spa is still an effective way to post-cure Formlabs resins, but if you need the absolute maximum properties from your prints, you should consider a cure chamber that has temperature-controlled heating and a 405 nm light source.

CONCLUSIONS

The results clearly show that the post-cured mechanical properties of parts printed with Formlabs resins on Form 1+ and Form 2 printers are maximized by the use of increased temperature and a 405 nm wavelength light source. This is not surprising, as Formlabs resins are uniquely engineered to work with Formlabs printers, which all use 405 nm lasers in the 3D printing process. Post-cure temperature should be limited by the HDTs of the resins, which means 60 °C for Formlabs Standard Resins. Limit the temperature to 45 °C for Formlabs Tough, Flexible, and Castable Resin. We have learned that the value of incident flux in a post-cure chamber should be in the range of 1.25 mW/cm^2 to achieve the best possible mechanical properties. Finally, the time necessary to achieve a "fully" post-cured part was determined for Standard Resins, Tough, and Castable Resins at the recommended post-cure temperature. Recommended post-cure parameters of time and temperature are listed in Table 2. Thick, bulky, solid parts will require more time than the recommendations listed in this table because they are slower to heat up to the proper temperature.

TABLE 2: RECOMMENDED 405 NM POST-CURE PARAMETERS FOR FORMLABS SLA RESINS

Resin	Temperature (°C)	Time (min)
Standard Resins	60	60
Castable	45	120
Tough	45	30
Flexible	45	60

REFERENCES

[1] J. G. Kloosterboer, *Network Formation by Chain Crosslinking Photopolymerization and its Applications in Electronics*, Electronic Applications Volume 84 of the series Advances in Polymer Science, Springer Berlin Heidelberg 1988, pp 1–61

[2] N. Decker, *Kinetic Study and New Applications of UV Radiation Curing*, Macromolecular Rapid Communications, 2002, 23, No. 18, pp 1067–1093

[3] M. Rubinstein, R.H. Colby, *Polymer Physics* (Oxford Univ. Press, New York, 2009), Chap. 6