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Impact of UV curing process on mechanical properties and dimensional accuracies of digital light processing 3D printed objects

Younghun Lee[1], Sungho Lee[2], Xing Guan Zhao[1], Dongoh Lee[1], Taemin Kim[1], Hoeryong Jung[1] and Namsu Kim[*1]

[1]*Department of Mechanical Engineering, Konkuk University, 120 Neungdong-ro, Gwangjin-gu, Seoul 05029, Republic of Korea*
[2]*SoC Platform Research Center, Korea Electronics Technology Institute, 25 Saenari-ro, Bundang-gu, Seongnam-si, Gyeonggi-do 13509, Republic of Korea*

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Abstract. In the last decade, there has been an exponential increase of scientific interest in smart additive manufacturing (AM) technology. Among the different AM techniques, one of the most commonly applied processes is digital light processing (DLP). DLP uses a digital projector screen to flash an ultraviolet light which cures photopolymer resins. The resin is cured to form a solid to produce parts with precise high dimensional accuracy. During the curing process, there are several process parameters that need to be optimized. Among these, the exposure time affects the quality of the 3D printed specimen such as mechanical strength and dimensional accuracy. This study examines optimal exposure times and their impact on printed part. It was found that there is optimal exposure time for printed part to have appropriate mechanical strength and accurate dimensions. The gel fraction and TGA test results confirmed that the improvement of mechanical properties with the increasing UV exposure time was due to the increase of crosslinked network formation with UV exposure time in acrylic resins. In addition, gel fraction and thermogravimetric analysis were employed to microscopically investigate how this process parameter impacts mechanical performance.

Keywords: additive manufacturing; DLP 3-D Printing; mechanical properties; dimensional accuracy, UV curing, acrylic resin

1. Introduction

Rapid prototyping, also known as three-dimensional (3D) printing, was developed in the late 1970s (Beaman 2001), (Ciraud 1972). 3D printing technologies have evolved very rapidly in recent years and have shifted apart from their traditional application field. The accessibility of 3D printers for both industrial and general public use has grown dramatically in the past decade.

At present, 3D printers with stereolithography apparatus (SLA), selective laser sintering (SLS), fused deposition modeling (FDM), and digital light processing (DLP) are the most widely employed as additive manufacturing methods in both academia and industry. Among these various 3D printer types, DLP is the most suited for the development of functional materials because liquid formulations allow for easy tailoring of the properties of the final printed object (Sun 2005), (Xia 2009), (Curr 2008). Peterson *et al.* reported an efficient method for producing objects comprised of spatially controlled and graded crosslink densities, resulting in different mechanical strengths, using a diacrylate-based photo resin, 3D printer, and DLP projector (Peterson *et al.* 2016). By controlling gradation in synthetic structures, tremendous advances in the development of metamaterials and functional devices have been proposed (Muller *et al.* 2003), (Pompe *et al*. 2003), (Jin and Li 2013), (Schulz *et al*. 2003), (Giunta *et al*. 2014), (Hadji 2017), (Wu and Ding, 2015). DLP 3D printers work similarly to SLA and use photosensitive polymers as build material. However, instead of laser, they use a dynamic mask, which is generated by a digital micromirror device (Hull 1986), (Sun *et al*. 2005). An ultraviolet (UV) projection system applied to a bottom-up DLP 3D printer was positioned underneath a vat with a transparent base, with the projection lens focused onto the center of the vat. During the DLP printing process, the UV resin was deposited, layer by layer, based on the prerequisite model, and simultaneously polymerized by a UV light (Zhou *et al*. 2013), (Mott *et al.* 2016). Typical UV resins used for DLP printers are a mixture of photoinitiator, monomers, and oligomers. The UV laser has two important characteristics, wavelength and intensity. For the UV resin photoinitiator to react correctly, it must be exposed to light of the correct wavelength and sufficient UV dose. Otherwise, the chemical reaction may not be sufficient. The UV dose of each layer striking the surface causes the photoinitiator to trigger the polymerization reaction. The UV dose is the amount of UV energy penetrating the resin, multiplied by the exposure time (Decker *et al.* 2001), (Park *et al.* 2009).

∗Corresponding author, Assistant professor
E-mail: nkim7@konkuk.ac.kr

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Table 1 Photosensitive material and the curing parameters used in experiments (All samples were cured under UV intensity of 75 mW/cm^2

UV resin	Layer thickness (μm)	Exposure time for each layer (s)
UV-curing Acrylic resin	50	2.5 (specimen A), 5 (specimen B), 10 (specimen C)
	100	5 (specimen D)

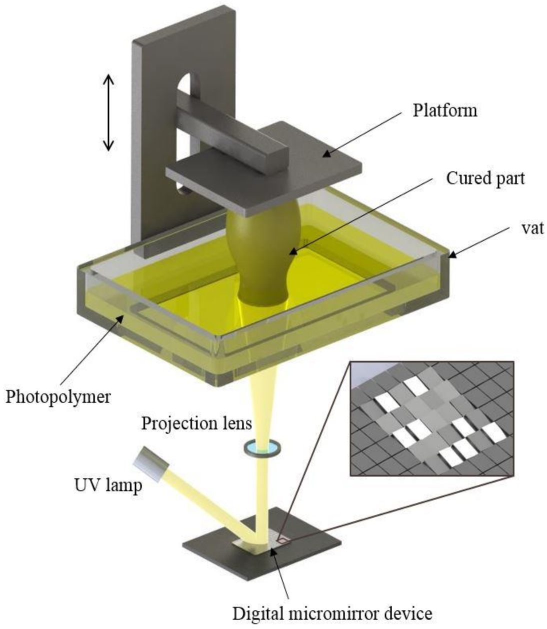


Fig. 1 Schematic of bottom-up DLP 3D Printer system

However, under this process, the presence of shrinkage and distortion within the prototype is a major source of error in the DLP process. Shrinkage, distortion, and poor mechanical properties, which affect the accuracy and quality of the printed parts, are considered a fatal drawback of the DLP process, and limits its application domain (Decker *et al*. 2001), (Park *et al.* 2009). The selection of suitable process parameters is critical for minimizing this drawback. Especially, since the process parameters are very important in the DLP type 3D printer, many researches have been carried out in order to optimize the process variables. (Gowda 2014), (Chiu 2015), (Ibrahim 2017). Chiu *et al.* proposed mathematical model which relates the mechanical properties with process parameters based on systematic experimental approach.

The objective of this paper is to investigate the effect of the UV exposure time on each layer. UV exposure time is identified as one of the most influential process parameters on the dimensional accuracy and mechanical properties of printed components. In addition, to quantify the total amount of UV exposure energy for printed sample, the UV dose (UVD) was defined by taking into account the UV exposure time, the exposure intensity, and the number of exposures depending on the number of layers. This study uses a tensile test to investigate the mechanical properties of specimens fabricated from DLP 3D printers cured under various exposure times. Mechanical strength is a critical material property because it significantly impacts the physical integrity and resistance to cracking, as well as determines the range of the use of parts printed on DLP-type 3D printers. Additionally, in order to investigate how changes in mechanical properties are related to UV curing, gel-fraction and thermogravimetric analysis (TGA) measurement were used.

2. Experimental details

DLP 3D printing was conducted using the CUBICON 3DP-110DS (Hyvision system, South Korea), equipped with a UV mercury lamp and digital micromirror device. The wavelength range of the light (Mercury lamp) was 385-650 nm, including the wavelength of the UV light at which the curing reaction was induced. The black photosensitive acrylic resin, provided by Hyvision System Inc., is used to fabricate the specimen. The influence of exposure time as well as the thickness of one layer on the mechanical properties of a part produced using acrylate resin was investigated.

To investigate the effect of exposure time on mechanical properties with 50 μm layer thickness, tensile specimens A, B, and C were fabricated with exposure times of 2.5, 5, and 10 seconds, respectively, under constant irradiation. The effect of layer thickness on the mechanical strength was also investigated by comparing the tensile strengths of specimens B and D, which were fabricated with layer thickness of 50, and 100 μm, respectively, for 5 s. In addition, specimen A and D were compared to investigate the mechanical strength. One specimen (A) was fabricated with 50 μm thickness and 2.5 s exposure and the other (D) was fabricated with 100 μm thickness and 5 s exposure time. The total time taken to fabricate them (specimen A and D) was the same but the exposure time as well as layer thickness were different. Even though the total time for fabricating sample A and D is not exactly the same due to the time for vertical movement and waiting before UV exposure, it was assumed that the time for fabricating sample A and D is the same by considering only the number of frequency for exposure to UV and the exposure time to UV in this study. These process parameters including specimen were summarized in Table 1.

Fig. 2 shows the test specimens fabricated by the DLP 3D printer according to ASTM standard D638-V at 26℃. After fabrication, the specimen was immersed in isopropyl alcohol (99.6%) for 15 min to clean out residual resin and dried at 26℃ in 15.7% relative humidity for 6 hours. All the samples were directly tested without any post curing.

Table 2 Mechanical properties of tensile specimen printed with varying UV exposure times

UV exposure time (s)	Tensile strength (MPa)	Yield strength (MPa)	Young's Modulus (GPa)	Stress before break (MPa)	Strain before break (%)
2.5	35.24±1.55	22.71±2.96	1.57±0.08	40.92±1.76	6.24±0.34
5 (50 μm layer)	53.55±0.59	30.95±1.50	2.35±0.05	53.52±0.79	5.96±1.20
5 (100 μm layer)	42.67±2.93	26.93±2.01	1.96±0.06	44.46±2.47	3.68±0.74
10	55.69±0.88	30.27±1.05	2.32±0.04	55.59±0.98	6.89±0.53

The tensile test was performed using a universal testing machine with a grip speed of 5 mm/min and a distance between the grips of 25.4 mm. At least five samples for each test were used to calculate the average value and observe the consistency. All tensile tests were carried out at 26℃ in 50% relative humidity. In order to investigate the dimensional accuracy, five geometry parameters, D1 – D5, were measured in the ASTM standard specimen by using Vernier calipers. The data for the dimensional accuracy at five different locations, as shown in Fig. 2(d), are compared to determine which process parameters are significant factors for dimensional error.

The gel fraction of the UV curable acrylic resin, after curing, was determined by soaking in toluene at 100℃ for 1 day. The sample amount for the gel fraction measurement was about 80 mg. The network polymer was removed by filtration and dried at 50℃ to measure the weight. The below equation was used to calculate the gel fraction

$$\text{Gel fraction (\%)} = \frac{W_1}{W_0} \times 100 \qquad (2)$$

where W_0 and W_1 are the weight before and after filtration, respectively. The measurement of gel-fraction is a convenient method of investigating the degree of polymer curing such as the fraction of crosslinked or network polymers. In addition, the burnout behaviors of the UV-cured resin were analyzed by thermogravimetric analysis (TGA; Perkin-Elmer TA) performed in a nitrogen environment. Cured samples, ranging from 4-5 mg, were heated from room temperature to 600℃ at a rate of 10℃ min−1.

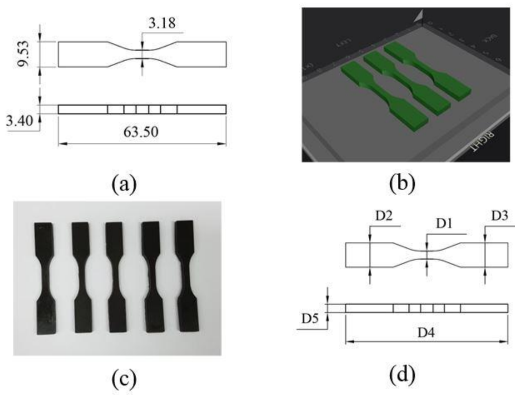


Fig. 2 (a) Test specimen of ASTM D638-V, (b) 3D modeling for printing process, (c) printed specimen according to the ASTM, and (d) the measurement point (D1–D5) for dimensional accuracy

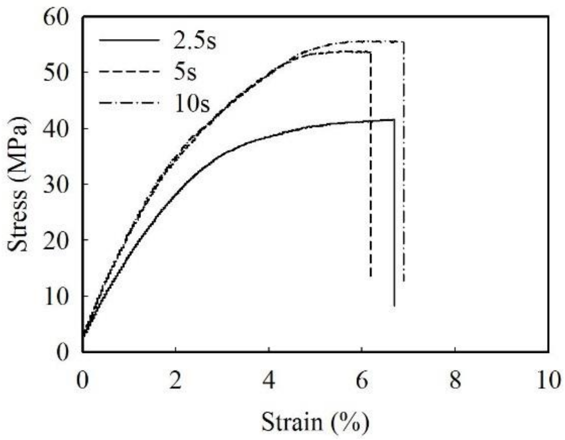
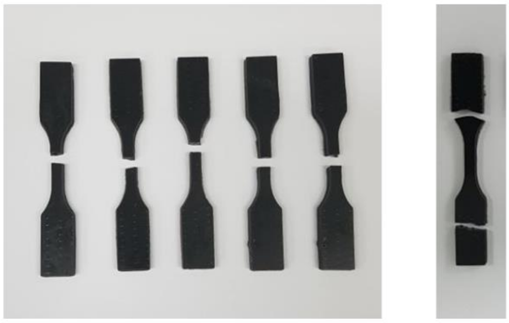


Fig. 3 Typical tensile stress-strain curves as function of UV exposure time



(a) (b)

Fig. 4 (a) Tensile tested specimen; specimen with 5 s UV exposure time (typical failure) and (b) failed tensile test specimen with 10 s UV exposure time (unexpected failure)

Table 3 Gel fraction with varying UV exposure times

UV exposure time (s)	UV intensity (mW/cm^2)	Gel fraction (%)
2.5		97.65
5	82	98.01
10		98.09

3. Results and discussion

Results in Fig. 3 show the representative tensile stress-strain curves of the fabricated specimen with varying exposure times, and show the effect of the varying exposure times on the mechanical properties. The overall mechanical properties with these exposure times are summarized in Table 2. Based on the results in Fig. 3, too low of an exposure time results in poor mechanical strength. It is reported that the UV curing process enables the formation of densely crosslinked networks by chain crosslinking.

Hence, the UV resin needs enough time to form a crosslinked network, resulting in increased mechanical strength. Moreover, during the printed specimen formation process, the photo-crosslinked layer cannot be attached to the previously cured layer when curing time is not long enough. Further, as the exposure time increases, it was found that mechanical properties of the specimen were improved to some extent. However, too much curing time decreases the ductility of the printed specimen, resulting in decreasing the strain before break. Sufficient UV exposure times increase the mechanical strength by producing a crosslinked formation, but can cause side effects that increase the brittleness of the material. The strain before break of the specimen with a 5 s exposure is larger than that of a specimen with a 10 s exposure. This brittleness also induces the failure phenomenon in an unintended place during the tensile test, as shown in Fig. 4(b). Even though specimens were fixed with same strength in the grip during the tensile test, more unexpected failures were found in specimens fabricated with 10 s UV curing process. It suggests that longer exposure time can enhance the mechanical strength, but overexposure may rather result in the brittleness of fabricated specimen. This change should be especially careful if the parts were used under loading condition. Longer UV exposure time can increase the density of cross-linking resulting in the improved mechanical strength. However, the brittleness can be increased due to the loss of chain mobility. This result is also consistent with previous reports (Mansour 2007), (Hague 2004). The images in Fig. 4(a) show a typical failure of tensile test specimen after test. Hence, it is critical to apply an optimized UV exposure process time to enhance the mechanical properties.

Next, additional experiment was carried out in order to investigate which of the thickness and UV exposure time further affect the mechanical properties. As shown in Fig. 5, the mechanical strength of specimen fabricated with 50 μm thickness (specimen B) is stronger than that of fabricated with 100 μm thickness (specimen D). It can be expected that the total number of frequency for exposure to UV when the sample B is fabricated is twice as much as that of the sample D. In addition, between specimen A and D, the mechanical strength of specimen D is stronger than specimen A. While the process time for both specimens are almost the same, the specimen A and D were fabricated with 50 μm thickness and 2.5 s exposure time and 100 μm and 5 s exposure time, respectively. It means that there is minimum time to be required to form a crosslinked network by UV exposure. These changes in mechanical properties with UV curing conditions should be carefully considered when designing parts. In addition, this property may also be utilized effectively such as producing graded and heterogeneous structures as reported (Muller e*t al*. 2003), (Pompe *et al.* 2003), (Jin and Li 2013), (Schulz *et al*. 2003). In order to investigate the impact of UV curing time on the crosslinked network density, the gel-fraction and TGA experiments were performed. The results in Table 3 show the gel fraction of the printed specimen as a function of UV exposure time. As the exposure time increases, the gel fraction also increases. The gel fraction increases rapidly with a UV exposure time of 2.5 to 5 s, and increases slightly with a time of 5 to 10 s in the samples. This indicates that more crosslinked networks are formed as the UV acrylic resin obtains more energy from the UV light. Hence, there should be optimized level of UV exposure time. To confirm the relation between the density of the crosslinked network and UV exposure time, TGA experiments were carried out with the same specimen. The TGA result summary for the printed specimen with different UV exposure times is given in Fig. 6 and Table 4. The weight loss curves, as a function of temperature, show the rate of thermal decomposition reaction and stability. The specimen with a highly crosslinked network shows better thermal stability.

Moreover, as shown in Table 4, the temperatures for each weight-loss percentile of longer UV exposure time is higher than that of shorter UV exposure time. This also confirms that the specimen with longer UV exposure time experiences less thermal decomposition owing to its higher thermal stability, compared to the specimen with shorter UV exposure.

Generally, parameters such as dimensional accuracy, warping, or shrinkage, and support requirements are used in order to quantify the accuracy of 3D printed parts. During our experiment, significant difference in warping or shrinkage was not found according to the UV exposure time.

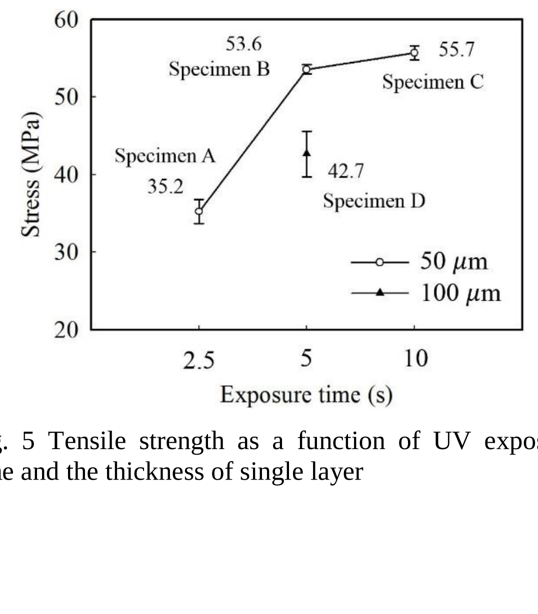


Fig. 5 Tensile strength as a function of UV exposure time and the thickness of single layer

Table 4 TGA analysis results for specimen with varying UV exposure times

UV exposure time (s)	5% weight loss temperature (℃)	10% weight loss temperature (℃)	30% weight loss temperature (℃)	50% weight loss temperature (℃)	Char residue (%)
2.5	174.4	349.1	406.7	434.5	11.71
5	181.5	354.7	408.3	434.7	10.27
10	206.0	358.3	409.4	436.3	10.43

Table 5 Dimension of CAD design of test specimen and the measurement results of printed specimen with varying UV exposure times

	D1	D2	D3	D4	D5
CAD design (mm)	3.18	9.53	9.53	63.50	3.40
UV exposure time (s)	AVG	AVG	AVG	AVG	AVG
2.5	3.05 ± 0.01	9.45 ± 0.03	9.44 ± 0.04	62.81 ± 0.07	3.04 ± 0.04
5	3.22 ± 0.03	9.57 ± 0.03	9.59 ± 0.02	63.00 ± 0.02	3.09 ± 0.05
10	3.38 ± 0.07	9.73 ± 0.03	9.75 ± 0.04	63.29 ± 0.10	3.10 ± 0.08

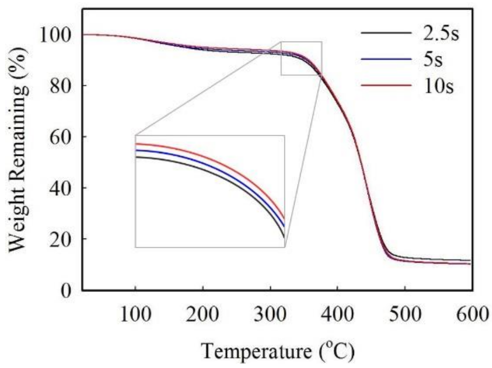


Fig. 6 TGA curves of UV cured specimen with varying UV exposure times

It was expected that our specimen for the tensile test was relatively thick, as well as a low aspect ratio, thus, there is no significant warping effect. However, the heat released by the exothermic reaction, as well as the radiant heat produced by the UV curing light, can cause warping or shrinkage during or after the process (Standury 2017). This means that a longer UV exposure time induces more heat, resulting in temperature rise. Hence, the impact of the temperature rise should be carefully considered, especially, in the case of large flat surfaces or long thin unsupported features. In order to investigate the impact of exposure time on the dimensional accuracy, the D1–D5 measurements of the fabricated specimen, as shown in Fig. 2, are summarized in Table 5. The dimensional accuracy is quantified by a parameter indicating the horizontal (D1–D4) and vertical (D5) directions. A minimum of five samples were printed for each set to decrease random error and increase the consistency of measurement. Based on the results in the table, it is found that the dimensional accuracies are closely related to the UV exposure time. During the DLP 3D printing process, the UV light was scattered at the interface between the vat (release film) and printed parts. The scattered UV light causes unintended UV hardening around the edge of the model. Because of the intrinsic nature of the bottom-up DLP process, this scattering occurs during the entire process, as shown in Fig. 1. Hence, longer UV exposure time induces more hardening around the edge by scattering and results in an increased horizontal size for the printed part. In the D1–D4 measurement results in Table 5, if the UV exposure time is prolonged, the horizontal measurement increases as the UV exposure time becomes longer. However, the impact of the UV exposure time on the vertical parameter (D5) dimensional accuracy is insignificant. The D5 measurement results, according to the different UV exposure times in Table 5, are not different when considering the standard deviation. Hence, depending on the UV exposure time, although there may be a slight difference in the hardness in the vertical direction, it can be concluded that there is no effect on the dimensional accuracy. The average value of dimensions with a 5 s exposure time most approximates the CAD design. Hence, in our system, the correct exposure time is determined to be 5 s for optimally built structures. Hence, the UV resin needs enough time to form a crosslinked network, resulting in increased mechanical strength.

4. Conclusions

The objective of this paper was to investigate the effect of UV exposure time, which is identified as one of the most influential process parameters in the DLP process, on the mechanical properties and dimensional accuracy of 3D printed components. Tensile strengths of specimens gradually increased with UV exposure up to 5 s, after which there is not much improvement. The gel fraction and TGA test results confirmed that the improvement of mechanical properties with the increasing UV exposure time was due to the increase of crosslinked network formation with UV exposure time in acrylic resins. In addition, it was found that excessive UV exposure induces the brittleness of the printed specimen, resulting in diminished mechanical strength. For dimensional accuracy, it was found that long exposure times resulted in the increase in the size of the sample due to light scattering around the edge of model. This phenomenon occurs during the entire process, from the first to the last layer, owing to the intrinsic property of the bottom-up DLP printing system. Hence, the UV exposure time should be carefully adjusted according to the printed component applications.

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