Study on impact of UV curing process of digital light processing 3-D printer on the mechanical properties and dimensional accuracies

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ABSTRACT

In the last decade, there has been an exponential increase of the scientific interest for smart additive manufacturing (AM) technology. Among the different AM techniques, the most commonly applied processes are digital light processing (DLP). DLP is a laser-based process that works with photopolymer resins, which react with the ultraviolet (UV) and is cured to form a solid in a very precise way to produce parts with high dimensional accuracy. However, because of the scattering effect when UV light passes through the transparent vat and different polymerization characteristics and curing depth of photopolymer resins, there are lots of parameters of DLP printers need to be optimized.

Among these, exposure time affects the quality of the 3D printed specimen. If it is not optimized, it brings about problems such as poor mechanical properties and poor dimensional accuracy. Therefore, this study examined optimal exposure time. With a same specimen and layer thickness, the photopolymer resin was exposed to the UV light in different times to evaluate the influence of it. The UV mercury lamp, 240 W and wavelength of 385-650nm is used. To investigate the effect of exposure time on the mechanical strength, the tensile strength and young's modulus were experimentally determined using universal material test machine.

1. INTRODUCTION

Rapid prototyping, also known as three-dimensional (3D) printing, was developed in the late 1970s. 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, Stereolithography apparatus (SLA), selective laser sintering (SLS), fused deposition modeling (FDM) and digital light processing (DLP) are among the most widely employed and investigated additive manufacturing methods in both academia and industry. Among these various types of 3D printer, DLP is the most suitable for the development of functional materials since using liquid formulations allows an easy tailoring of the properties of the final printed object. DLP 3D printers work similarly to SLA and use photosensitive polymers as build material. However, instead of laser they use dynamic mask, which is generated by digital mirror device is used. An ultraviolet (UV) projection system 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 is deposited layer by layer based on the prerequisite model, and simultaneously polymerized by an UV laser. Typical UV resins used for DLP printers are the mixture of photoinitiator, monomers, oligomers. UV laser has two important characteristics which are wavelength and intensity. For the photoinitiator of UV resin to react correctly, it must be exposed to light of the correct wavelength and of sufficient UV dose. Otherwise, the chemical reaction may not happen sufficiently. The UV dose of each layer striking the surface causes the photoinitiator to trigger the polymerization reaction. UV dose is the amount of UV energy penetrating the resin, multiplied by the exposure time.

Table 1. Photosensitive material and the curing parameters used in experiments

Photopolymer	Exposure time for each layer (s)	Layer thickness (mm)
UV-curing Acrylic resin	2.5, 5, 10	0.05

However, under this process, the presence of shrinkage and distortion within the prototype is one of the major sources of error in the DLP process. This shrinkage, distortion and poor mechanical properties, which affect the accuracy and quality of the part, are considered as fatal drawback of the DLP process and limit its application domain. Selection of suitable process parameters is critical to minimize the drawback.

The objective of this paper is to investigate the effect of UV exposure time for each layer, which is identified as one of the most influential process parameters, on dimensional accuracy and the mechanical properties of DLP printed components. This study uses tensile test to compare the mechanical properties of specimens fabricated from DLP 3D printers cured under various exposure times.

2. EXPERIMENTAL

DLP 3D printing was conducted using CUBICON 3DP-110DS (Hyvision system, South Korea) equipped with UV mercury lamp and digital micromirror device. The wavelength range of UV light is 385-650 nm. The black photosensitive acrylic resin which was provided by Hyvision system Inc. is used to fabricate specimen. The influence of exposure time on the mechanical properties of the part produced using acrylate resin was investigated. The main curing parameters used in experiments are listed in Table 1. To investigate the effect of exposure time on the mechanical properties, tensile specimens were fabricated subject to different exposure times with constant irradiation as shown in Table 1. A layer thickness of 50 μm was chosen for all building processes and exposure times were 2.5, 5 and 10 seconds for each layer. Figure 1 shows the test specimens fabricated by DLP 3D printer according to the ASTM standard D638-V at 26 °C. After fabrication, specimen was immersed in isopropyl alcohol (99.6 %) for 15 minutes to clean out residual resin and was dried at 26 °C and 15.7 % relative humidity for 6 hours. All the samples were tested directly without any post curing.

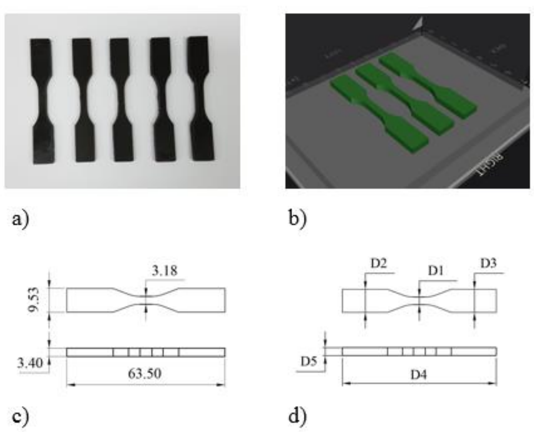

Figure 1. The test specimen ASTM D638-V a) actual specimen, b) three-dimensional model, c) dimensions, d) measurement points

The tensile test was carried out 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 average value and observe the consistency. All tensile tests were carried out at 26 °C and 15.7 % relative humidity.

In order to investigate the dimensional accuracy, five geometry parameters, D1 – D5, in ASTM standard specimen were measured by using vernier calipers. The data for dimensional accuracy at five different locations as shown in Figure 1(d) are compared to find out which process parameters are significant factors of the dimensional error.

3. RESULTS AND DISCUSSION

Figure 2 shows the tensile stress-strain curves of fabricated specimen with different exposure times. Based on results in Figure 2, lower exposure time results in poor mechanical strength. It is due to that the photo-cross-linked layer cannot be attached to the previously cured layer. As the exposure time increases, it was found that the mechanical properties of specimens were improved to some extent.

The obtained stress strain curves show that the tensile strength of the specimens gradually increases as the exposure time increases. The strength values with different exposure time are summarized in Table 2. The logical reason for this behavior is the increased degree of polymerization and cross-linking density of the resin when sufficient energy is supplied to the resin. It is well-known that increasing the crosslinking density leads to an increase in the mechanical properties. However, during the tensile test, it was found that the brittleness increased in the latter case due to frequent breakage of grip part of the specimen fabricated with too long exposure time as shown in Figure 3 (b).

Table 2. Photosensitive material and the curing parameters used in experiments

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
5.0	53.55±0.59	30.95±1.50	2.35±0.05	53.52±0.79	5.96±1.20
10	52.86±0.88	30.27±1.05	2.32±0.04	52.83±0.98	6.36±0.53

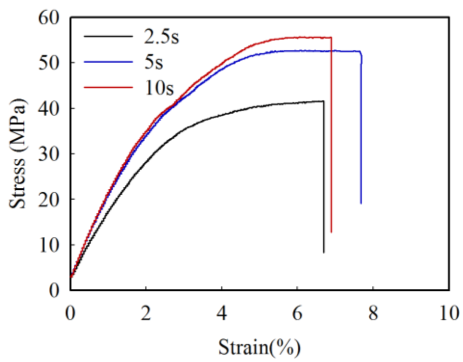

Figure 2. Tensile stress-strain curves for different UV exposure time for each layer

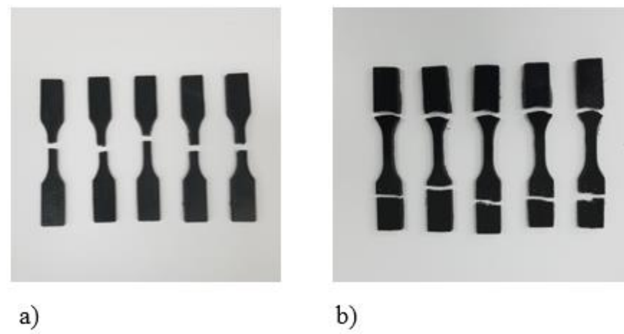

Figure 3. tensile tested specimen that cured each layer for a) 5s, b) 10s

In order to investigate the impact of exposure time on the dimensional accuracy, measurement of D1 – D5 of fabricated specimen are summarized in Table 3. A minimum of five samples were printed for each set to decrease random errors and increase the accuracy of measurement. Dimensional accuracies are closely related to the UV exposure time. During DLP 3D printing process UV light was reflected on the previously printed parts, thus dimension of the CAD design of test specimen was expanded to the plane of vat which is vertically exposed to the UV light. The average value of dimensions with exposure time of 5 second is most approximate the CAD design. As a result, the longer the UV exposure time, the larger the overall measurement value. As a result, the correct exposure time is 5 seconds for optimally built structures. It is found that this tendency of the dimensional accuracy is different from the tendency of the mechanical strength according to the UV exposure time.

4. CONCLUSION

The objective of this paper is to investigate the effect of UV exposure time for each layer, which is identified as the most influential process parameter, on mechanical properties and dimensional accuracy of DLP printed components. Tensile strengths of specimens are gradually increased with UV exposure time. However, it is also found that the excessive UV exposure induces the brittleness of printed specimen

Table 3. Dimension of CAD design of test specimen and the result of the dimensional measurement

	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±0.0147	9.45±0.0340	9.44±0.0426	62.81±0.0723	3.04±0.0435
5	3.22±0.0337	9.57±0.0300	9.59±0.0248	63.00±0.0206	3.09±0.0500
10	3.38±0.0747	9.73±0.0293	9.75±0.0432	63.29±0.0977	3.10±0.0776

resulting in diminishing mechanical strength. For dimensional accuracy, long exposure times have been found to increase the size of the sample due to long curing time. Hence, UV exposure time should be carefully adjusted according to the applications of printed components.

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BIOGRAPHIES

YoungHun Lee was born in Seoul, Republic of Korea in 1993. He is undergraduate student in Department of Mechanical Engineering at Konkuk University, Seoul, Republic of Korea, where he entered in 2013. His research interests include additive manufacturing system and Stereolithography-based rapid prototyping. In recent years, he focused on UV curing process of digital light processing.

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