Exposure Time Variation Method Using DMD for Microstereolithography*

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Abstract
In stereolithography, parts are fabricated by curing photopolymeric resins with light. The application of stereolithography can now be extended to a very small scale. The process, called microstereolithography, can fabricate parts on a microscale without any further consideration of geometry complexity. In particular, projection-type microstereolithography can perform quite rapid fabrication that cures a specific cross section in one exposure to light without movement. However, in the case where the light source has a nonuniform intensity or an aberration caused by its optics, the part might have some distortion, and this is commonly the case. Because the material experiences shrinkage when it is cured, the light intensity over the entire cross section should be uniform. This study utilizes a Dynamic Mirror Device, which is mainly used for beam shaping, to control the beam intensity also. This control makes the beam intensity profile flat and reduces the distortion to a great degree. This paper presents the concept of an exposure time control method that makes the beam intensity uniform, and it also presents some experimental results.

Key words: Microstereolithography, Projection Stereolithography, Dynamic Mirror Device, Exposure Time Variation Method

1. Introduction

Microstereolithography uses layered manufacturing technology to fabricate a 3-dimensional structure through photocurable resin. It can fabricate a microstructure automatically without any further consideration of the geometry complexity. The materials it is applied to are photocurable resins, which are liquid state monomers that are transformed into the solid state by photopolymerization when exposed to light with a certain wave length. More specifically, such photopolymerization is begun by an initiator. (1)

The most common type of this technology is spot curing, which focuses the energy emitted from a light source onto a small spot, and then moves the spot along the contour lines of a part and fills it inside. (2,3) The other type is image light projection, in which an area is cured with a single shot. (4,5) The latter type is used to cure a small area (typically 1–2 mm²) all at once by using a Digital Micromirror Device (DMD) (6) and a lamp light source. The DMD used in this study had 1024 × 768 arrays of micromirrors at a 13.68 μm pitch. A cross section of a part can be cured by one or several shots, depending upon the area to be cured. Projection-type microstereolithography performs faster fabrication and offers good resolution, but the cured part can be distorted if the energy level of the entire projected area...
is not uniform. Most resins shrink when they are photopolymerized. A difference in light intensity will lead to a difference in curing speed, which results in distortion. Therefore, by making the intensity uniform, the part accuracy can be increased. The aim of this study is to develop a technology that makes the light uniform in order to minimize the part distortion. This is achieved using a local energy exposure control method that requires a DMD.

2. Experimental apparatus

A high-pressure mercury UV lamp (INNO-CURE 100N, Lichtzen Co., S. Korea) was selected as the light source of the system. It has an output power of 2 W UV and a peak wavelength of 365 nm. Light emitted from the lamp is transmitted through optical fiber and focused on a DMD (0.7 XGA 12° DMD, Texas Instruments Co., USA) after passing through the collimating lens of the lamp system. A DMD is an array of micromirrors, each of which can be controlled so that it either reflects the light or does not. A series of black-and-white bitmap images can be an input for the DMD. A white pixel indicates a reflected position and a black pixel indicates no reflection. The DMD can process up to 32,000 image frames in one second. For example, when the DMD has a black star image on it, then only the mirrors corresponding to the white pixels are set to reflecting positions. The reflected light is therefore shaped as a star figure regardless of the shape of the incoming light source. Shaped light from the DMD passes through a shutter (VMM-D1, Uniblitz Co., USA) that controls the overall on-and-off exposure process. After the shutter, there is a lens (f200 fused silica spherical lens, Optosigma, USA) that reduces the beam size to fit an objective lens (CFI Plan Flour 4X N.A. 0.13, Nikon, Japan). The objective lens is used to reduce aberrations and focus the light. There is a resin vat on the xy stage (PL-100, TechMac Co., S. Korea) and a platform is submerged in the vat to make a new layer. The system keeps the entire optical path static because of the optics’ high degree of sensitivity. The platform and xy stage constitute the only moving component needed to fabricate a large 3D structure. Fig. 1(a) shows a schematic of the light delivery system described above, and Fig. 1(b) shows the actual experimental apparatus.

For fabrication, the actual part geometry should be modeled by a 3D CAD system. The model should be saved in the STL file format, which is the de facto standard in rapid prototyping. The STL file format represents the surfaces of a 3D solid model as a triangular net. Despite the shortcoming of lacking topological information, the STL file format is widely used owing to its simplicity. Much research has been conducted to improve or replace this file format. To obtain layered fabrication information, the STL model should be sliced along a horizontal plane, with one or more loops in each slice. To prepare a black-and-white bitmap image for a DMD, the insides of the loops are painted white, and the holes or outer loops are painted black. Since the white of this bitmap image represents the corresponding pixel of the micromirror of the DMD, it will reflect the
incoming light to the lens. The build controller is software that fabricates the part, repeating the recoating, curing, and moving processes according to the bitmaps and process parameters.

The recoating process forms a new liquid resin layer on the previously built layer. First, to perform the recoating, the platform is dipped deeply enough to coat a sufficient amount of the new resin on the previously built layer, and it is then elevated in order to form a precise layer thickness. A waiting period then ensues until the resin surface flattens out. The curing process is done in order to solidify the liquid resin; in the process, the shutter is opened to pass the formed light from the DMD. The curing time is the most important factor in this process because too short an exposure will result in undercuring, and too long an exposure will result in overcuring. After the curing process, the xy stage moves to the next curing position. Fig. 2 shows the fabrication process.

3. Exposure time variation

The system described above produces the output shape shown Fig. 3(b) when the DMD image is a square such as the one shown in Fig. 3(a). The difference between these two is caused by the nonuniform light intensity in each pixel, as shown at Fig. 3(c). This distortion
is mainly caused by the nonuniform intensity profile of the light source and aberration of the optics, and these two factors give the profile a more convex shape at its center.

To make the light intensity uniform, this paper introduces an exposure time variation technique that closes each of the mirrors according to the excess energy. With this method, the entire area to be cured can receive uniform energy during the curing process. However, the beam intensity shown in Fig. 3(c) is measured by a laser beam profiler (BeamMage CCD12-UV, Gentec-EO, Canada) and has some noise. To obtain a precise exposure compensation factor, this noise must be filtered.

A modified average filtering technique is applied in this study. Average filtering is a digital signal processing technology that alters each pixel by taking into account the average value of neighboring pixels. With this technique, however, noise is still included in the average value, and it may thus spoil the normal signals. This study therefore implements a filtering technique that can preserve the original signal without large noise. All the pixels in the measured data are filtered by the modified average filter shown in equation (1).

\[
I'_{ij} = \begin{cases} 
I_{ij}, & |I_{ij} - a_{ij}| < \alpha d_{ij} \\
\frac{a_{ij}}{d_{ij}}, & |I_{ij} - a_{ij}| \geq \alpha d_{ij}
\end{cases}
\]  

(1)

Here, \(I_{ij}\) denotes the light intensity measured at pixel \(i,j\); \(I'_{ij}\), the intensity profile at pixel \(i,j\) after filtering; \(\alpha\), the filter strength; \(a_{ij}\), the average intensity around pixel \(i,j\); and \(d_{ij}\), the standard deviation around pixel \(i,j\).

The above-mentioned technology replaces each pixel intensity value with an average value when the difference between the pixel intensity and average intensity around the pixel is greater than the scaled standard deviation of the intensity around the pixel. Further, it does not change the pixel intensity in any other case. Thus, by using this algorithm, the noise signals are rejected and the normal signal is preserved. A square window is applied to compute the local average and standard deviation around a specific pixel, and equations (2) and (3) show how these values are computed.

\[
a_{ij} = \frac{\sum_{m=1}^{w-1} \sum_{n=1}^{w-1} I_{m,n} - I_{ij}}{w^2 - 1}
\]  

(2)

\[
d_{ij} = \sqrt{\frac{\sum_{m=1}^{w-1} \sum_{n=1}^{w-1} (I_{m,n} - I_{ij})^2}{w^2 - 1}}
\]  

(3)

where \(w\) stands for the window size of averaging.

Fig. 4 shows the filtering results when \(\alpha\) is 1 and \(w\) is 5. Making the light intensity uniform over a cross section is important in order to reduce the distortion of the cured part. To achieve this, this paper introduces an exposure time variation method that employs a DMD and gray scale images. The main idea of this approach is to reduce the exposure time where the light intensity of the pixel is stronger than the reference intensity. The exposure time is inversely proportional to the excess amount of light. The reference exposure should exceed the critical exposure to initiate photopolymerization. It can also be adjusted to obtain an appropriate curing time. To create an exposure time difference by each pixel, a grayscale image, which implies an exposure time, should be created first. The light irradiation time is set according to the brightness of the pixel.
A brighter pixel means longer irradiation. That is to say, pixels corresponding to a nonfeatured region will be set as black. Pixels with the reference intensity will be set as white, and pixels with more intense light than the reference intensity will be set as gray. Further, a pixel becomes darker when the difference between the reference and pixel intensities increases. Gray scaling of the image can be performed using equation (4).

\[ G'_{i,j} = c \frac{r}{I_{i,j}} B_{i,j} \]  

(4)

where \( G'_{i,j} \) denotes the new grayscale image at pixel \( i, j \); \( c \), the grayscale level of white; \( r \), the reference exposure; and \( B_{i,j} \), the black/white bitmap image at pixel \( i,j \).

Fig. 5 Fabrication using the exposure time variation method
Fig. 6 Exposure time variation in 3D model

<table>
<thead>
<tr>
<th></th>
<th>Left needle diameter</th>
<th>Right needle diameter</th>
<th>deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal</td>
<td>238  μm</td>
<td>222  μm</td>
<td>16  μm</td>
</tr>
<tr>
<td>Grayscale</td>
<td>222  μm</td>
<td>220  μm</td>
<td>2   μm</td>
</tr>
</tbody>
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Table. 1 Microneedle diameter deviation comparison

Fig. 5(a) shows the grayscale image generated by equation (4) with the filtered light intensity profile $I_{ij}$, which was obtained from image Fig. 3(a). By loading this image on a DMD, the pixels will reflect light to the same degree as the brightness of the image. The fabricated square with a grayscale image is shown in Fig. 5(b). The measured light intensity is shown in Fig. 5(c), in which the uniform distribution of the light intensity indicates that the proposed exposure time variation method works as intended.

Fig. 6 shows a 3D model fabrication example in order to compare a normal case with the case in which the exposure time variation method is applied. The model in the example is a pair of microneedles. Fig. 6(a) shows a cross-section image of the columns of the microneedles, and the corresponding UV beam profile is shown in Fig. 6(b). The part
fabricated without exposure variation is shown in Fig. 6(e). As can be seen in the figure, there is a difference in the thickness of the needles, and the right-hand-side needle bends to one side. These problems are caused by the difference in the light intensity applied for each needle. In contrast, in the needle pair produced by the method proposed in this study, shown in Fig. 6(f), it can be seen that the exposure time variation method can make the light intensity uniform, and it produces very precise needle without bending.

4. Conclusion

This research introduces an exposure time variation method to increase the fabrication accuracy of microstereolithography. In an experiment performed with actual materials, it was shown that a nonuniform light intensity produces distortion when a photopolymeric resin is cured. The beam intensity was measured by a beam profiler and was filtered by a modified average filter. An equation was introduced for the generation of a grayscale image. The image also indicated how much exposure time was required for each pixel. As the results suggest, the proposed method makes the light profile uniform and greatly increases the geometric accuracy of the fabricated part. The proposed method was verified by using a simple square feature, and it was applied to an instance of microneedle fabrication to show its feasibility in actual applications. The method presented in this study can be applied with a DMD that can process grayscale images. In the future, real time processes of light intensity compensation technology will be studied in order to increase the method’s practicality.

Acknowledgements

This research was supported by a basic science Research Program through the National Research Foundation of Korea (NRF), which is funded by the Ministry of Education, Science and Technology (2010-0013209). This work was also supported by a Korea Science and Engineering Foundation (KOSEF) grant funded by the Korean government (MEST) (NO. RO1-2008-000-20568-0).

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