REAL TIME MONITORING OF EXPOSURE CONTROLLED PROJECTION LITHOGRAPHY

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ABSTRACT: Exposure Controlled Projection Lithography (ECPL) is a stereolithographic process in which lens shaped features are fabricated from Photopolymer resin. During the fabrication process, a dynamic mask is used to control and project radiation patterns through a transparent substrate onto the photopolymer resin to grow the features progressively from the substrate surface. We present a novel method to monitor the photopolymerization process in real-time with spatial resolution in a plane perpendicular to the growth of polymerization. A transparent Spatial Light Modulator (SLM) was incorporated into our Interferometric Cure Monitoring (ICM) system, an interferometric monitoring system which is used to measure the cured part height. The introduction of SLM enabled multiple point which could not be achieved by the traditional manually operated iris. This improved ICM system fulfilled the need of selectively scanning the curing area and estimating the height and width of the cured part at a specific region of interest. This multiple-point-selective monitoring approach is experimentally validated to measure the height at different locations of the cured part in real time, and also the lateral dimensions of the cured part at the substrate level by a scanning process controlled by the SLM.

1. INTRODUCTION

Exposure Controlled Projection Lithography (ECPL) is a stereolithographic process in which 3D features are fabricated by radiating beam of light with controlled profile patterns onto a bath of photopolymer resin. Lithography processes traditionally use a scanning curing laser with a bath of photopolymer resin to progressively build the 3D features layer by layer. In contrast, Limaye & Rosen[1], Sun et al[2], Chatwin[3], Monneret et al. [4], and Jariwala et al. [5] investigated building 3D features with dynamic masks which control the radiating patterns of the exposure light source onto photopolymers instead of curing laser scanning process. The ECPL system controls the curing light source with a dynamic mask and projects this curing source into the resin chamber, and the fabricated 3D features are controlled by changing the shape and intensity of these dynamic curing light masks. The ECPL process differs from the other mask projection processes in that the radiation pattern is projected upwards through a transparent substrate into the resin bath where the part is cured. Jariwala et al. [6] [7] proposed an ECPL process planning method which utilizes chemical photopolymerization models of resin to estimate the cured part height. A sensor called the Interferometric Curing Monitoring (ICM) system was then proposed by Schwerzel et al. [8] to improve the accuracy of 3D feature fabrication. This paper provides a method to monitor the lateral dimensions and height distribution of the cured part during the photopolymerization process. This method fulfilled the need of real time monitoring of part lateral dimensions during the curing process which enables closed loop control as shown in [9] to improve greatly ECPL process accuracy. Experimental results are presented to validate this method.

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2. SYSTEM OVERVIEW

A schematic of the ICM system and the ECPL system is shown in Figure 1. The ICM system includes part (1) to (8), and the ECPL system includes part (9) to (12). During the curing process, the curing light from the UV source passes through the dynamic mask generator (DMD) which forms the curing light beam with its cross-section profile being controlled. The projection system focuses the light onto the resin chamber, and the light passes through the bottom transparent substrate of the resin chamber into the photopolymer resin to begin the curing process. The dynamic mask and exposure time determine the 3D dimensions of the part.

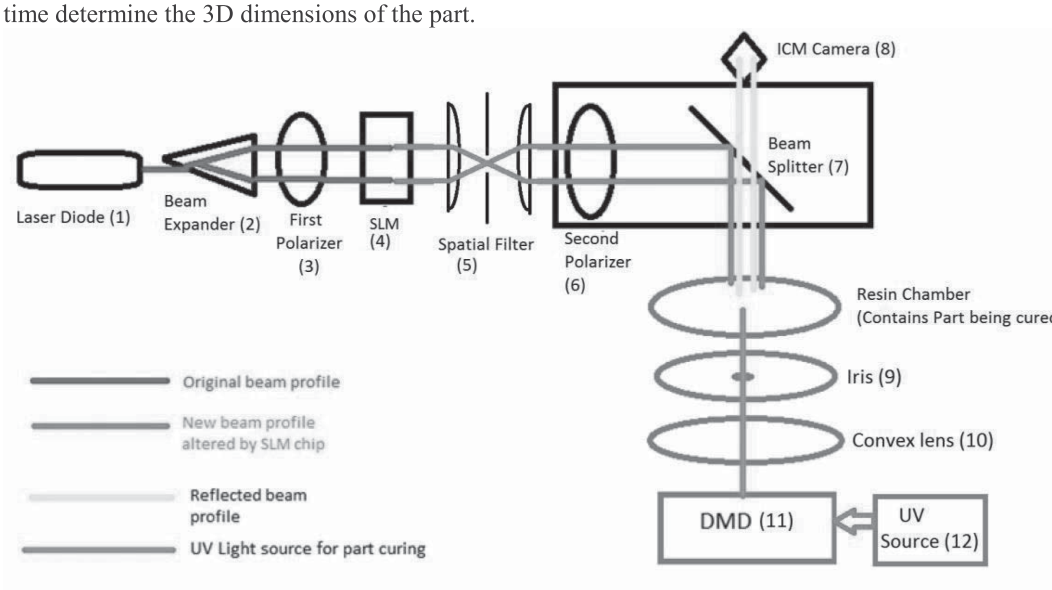

Figure 1. Schematic of ECPL system and ICM system

2.1 ECPL system

The radiation source is an Omnicure S2000 UV spot curing system produced by Lumen Dynamics. The source outputs radiation with a wavelength of 365 nm, which is the wavelength at which the photoinitiator is sensitive. The resulting beam is piped through a light guide to the dynamic mask generator. The dynamic mask generator is Digital Light Innovations' CEL5500 Digital Micromirror Device (DMD) which has an array of 1024x728 mirrors with a pitch of 10.8 μm. The DMD is controlled as a secondary monitor using Microsoft PowerPoint software. The projection system is composed of a 25 mm diameter convex lens with 50 mm focal length and an iris which can open a pinhole with diameter ranging from 0.8-12 mm. This projection system is used to sharpen the acutance of the dynamic mask. The resin chamber consists of two glass slides separated by spacers of known thickness. The photopolymer resin is loaded between the two glass slides. This photopolymer resin crosslinks inside this resin chamber when exposed to UV radiation.

2.2 ICM system

The Interferometric Cure Monitoring (ICM) system is based on a Mach-Zehnder interferometer and is described in detail in [8]. A coherent laser is directed, through a beam expander, a polarizer, an SLM chip, a spatial filter, another polarizer, and beam splitter, at the resin chamber. Light reflecting off of the top and bottom surface of the resin chamber's two transparent bounding surfaces reflects through the beam splitter and into the camera. Due to the phase difference between the light coming from the top surface and the light coming from the bottom surface an interference pattern is observed by the camera.

The laser source consisted of Thorlabs CPS532 laser diode. The purpose of this diode is to provide the coherent laser light required for interferometry. The purpose of the beam expander is to expand the narrow beam produced by the laser source such that the light output is capable of covering the entire curing region in light such that any point around the curing region can be analyzed by the camera. The Spatial Light Modulator (SLM) system is composed of a polarizer, an SLM chip, a spatial filter, and another polarizer. The SLM chip with two polarizers on each side of it functions as a movable iris. The spatial filter is added to reduce the diffracted laser patterns which are created when the laser passes through the SLM chip. The SLM system has two functions: to reduce the laser beam size that for use as a point sensor, and to enable moving the point sensor laterally to other points in the resin chamber. These two functions enable the real-time monitoring of the photopolymerization process. The ICM camera, BASLER acA2500-14gm GigE, captures the intensity of the interference pattern that is produced by the interference between the reference beam (reflected from the cover slide) and the signal beam (reflected from the cured part).

3. ICM WORKING PRINCIPLE

The ICM system utilizes the principles of interferometry to estimate the height of the part cured in the resin chamber in real time. The camera records the interferogram produced by the phase difference between the light reflecting from the top surface of the resin chamber and the bottom surface of the resin chamber. The thickness of the resin chamber results in steady state optical path offset which equates to a constant phase shift. The curing process causes the photopolymer resin to increase density as it crosslinks, and this changes the refractive index of the resin in the resin chamber. The cured part height can be expressed as a function of the phase shift which is a function of the optical path. Schwerzel et al. [8] proposed the equation for this phase shift as:

$$shift = \frac{2*\Delta n*t}{\lambda} \tag{1}$$

where Δn is the change in refractive index of cured resin, t is the thickness of the cured part, and λ is the laser wavelength. A linear relationship was experimentally determined between phase shift and the cured part height [8], which provides the fundamental basis for estimating cured part height based on the phase shift of the interference pattern, captured by the ICM camera.

4. EXPERIMENT PROCEDURE

A series of experiments was performed to demonstrate the capability of the SLM-based ICM system to monitor the lateral extents of a curing part, as well as the part's height distribution, in real time. The experiment reported here utilized a DMD image of 350x768 pixels to cure a rectangular part for 25 seconds. The SLM sampled a 4x5 array of small regions, each of which was 10x10 pixels on the SLM in size. These regions were spaced 25 pixels apart and each column of regions was offset 5 pixels from the previous column. The intensity changes of the interference patterns at the center of each region were recorded by the ICM camera as a video file during ECPL operation. Figure 2 shows the positions of the 20 detecting points on the ICM video with the blue rectangle indicating the irradiated region. Background noise was removed by subtracting the intensity measured at a point far away from the irradiated region from the interferograms recorded at each sampled point.

It was hypothesized that interferograms recorded at sampled points within the irradiated region (points 5, 6, 9, 10 and 14) would indicate significant curing, while at sampled points outside of the irradiated region (1, 2, 3, 7, 11, 13, 15, 17, 18, and 19), no curing would be indicated. As an indication of curing, an interferogram will have well defined, large amplitude oscillations with a period of approximately 5 seconds. At other points, interferograms with small amplitude or random oscillations will be observed.

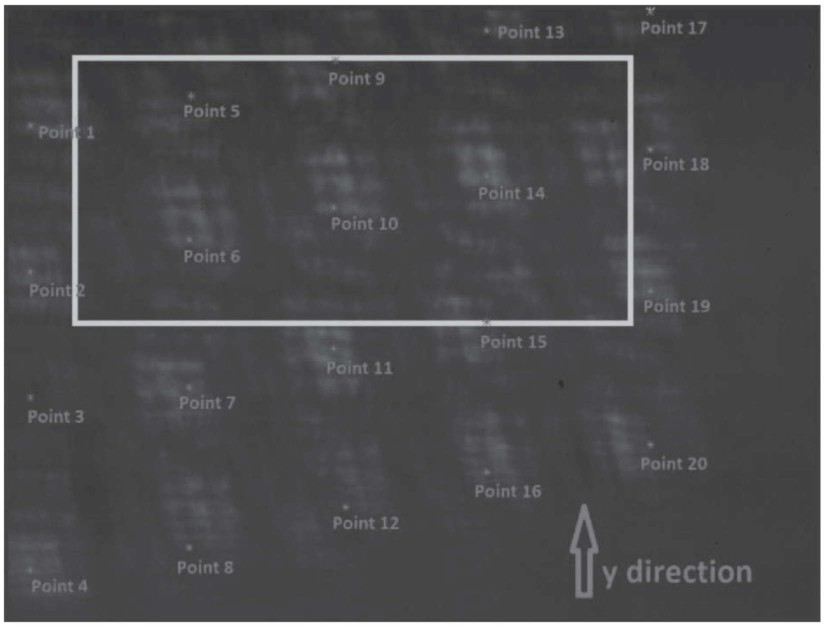

Figure 2. Points analyzed in the experiment and the curing region.

6. RESULTS AND DISCUSSION

The interferograms were analyzed, and the total phase shift and average amplitude of the well defined oscillations were recorded. Figure 3 shows the interferograms recorded at sampled points 6, 7, 10, and 12. As expected, the interferograms from points 6 and 10 exhibit large amplitude oscillations, while at point 12 the interferogram was flat. At point 7, which is close to the irradiated region, small amplitude oscillations were observed. The phase shift information is shown in Figure 4, where the number of oscillations at each sampled point is indicated in a 2D layout as a Matlab meshgrid plot. According to the specifications on the camera, one pixel on the

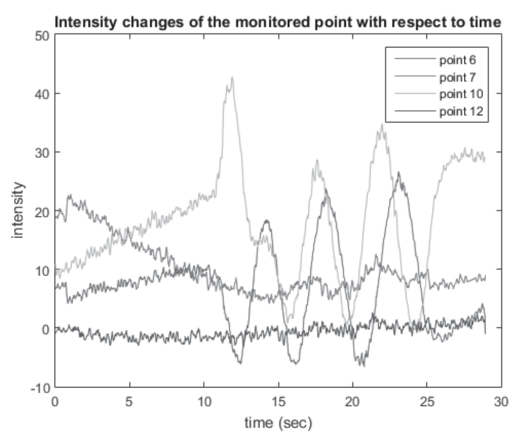

Figure 3. Interferograms at points 6, 7, 10, 12.

ICM camera corresponds to 2.2 μm. Since the original ICM recorded video was resampled from 2592x1944 to 648x486 pixels (i.e., by a factor of 4), and the average lateral pixel distance between the closest two detecting points observed on the ICM was 14.5 pixel, the lateral resolution in this experiment was 127.6 μm.

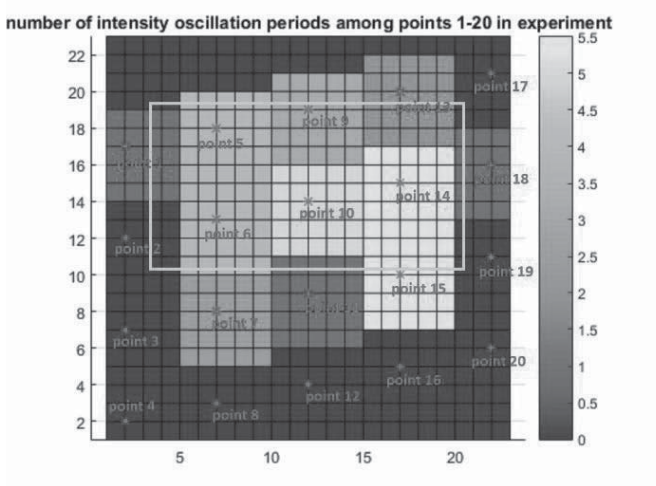

Figure 4. Number of oscillation periods at sampled points.

The meshgrid figures could help determine the shape and size of the cured part after the curing process. Figure 4 showed the meshgrid figure with the blue rectangle indicating the irradiated region. From Figure 4, the bottom edge of the part appears to lie between points 7 and 15, since 5.5 periods were observed at point 15, while only 2.5 were observed at point 7. The top edge appears to lie between points 5 and 13. An empirical scaling relationship was determined to estimate lateral dimensions in ICM images. Using this relationship, the vertical distance between points 7 and 13 is approximately 1531 μm, which is somewhat more than the measured size of the cured part using the confocal microscope, which was 1150 μm. The discrepancy can be due to inherent cross-talk between the signals from separate points resulting from internal reflections. The errors can be possibly reduced by further increasing the distance between the interrogation points and by refining the design of the resin chamber to reduce the effect of internal reflections. This experiment demonstrated the capability of estimating lateral part dimensions using the proposed SLM-based sampling strategy in the ICM system.

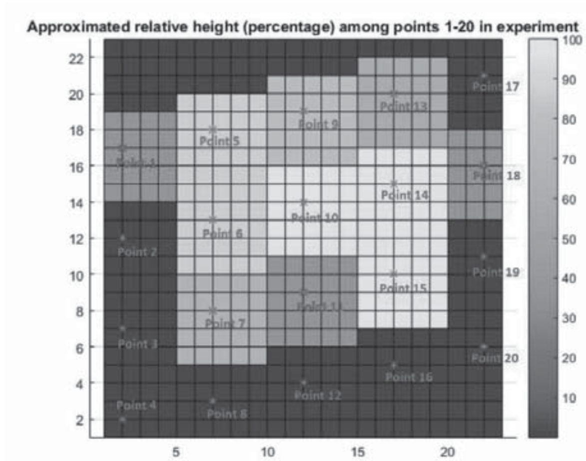

Figure 5. Relative height (percentage of the maximum height) distribution of the cured part

In addition to lateral dimensions, the height distribution of the cured part can be estimated also. From previous work [9], a linear relationship is expected between the natural logarithm of the phase angle and the cured part height. Based on this expected linear relationship, the relative height of the cured part at each sampled point has been calculated and plotted as a percentage of the maximum cured part height. The Matlab meshgrid plot of relative height distribution is shown in Figure 5. This height distribution agreed reasonably well with part height measurements taken with a confocal microscope.

7. CONCLUSIONS

This paper presented a method to measure lateral dimensions and relative height distribution of the cured part during the photopolymerization process in the ECPL process, based on using an SLM to measure the interferogram at selected locations. The measurements taken from an array of small ICM beams coincided with confocal microscope measurements, which were believed to be accurate. More accurate models of the correspondence between pixels in the ICM camera and dimensions are needed in order to estimate actual part sizes. However, the accuracy of the models was good enough to validate the part measurement method. The resolution of the ICM beam measurements could be further improved by using a larger sampling point array. Additionally, the sampling array could be translated laterally to more completely sample the entire resin chamber region and to sample the chamber at a higher spatial resolution (albeit at a lower temporal resolution).

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