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Measurements of flow distribution in a thin resin layer during ultraviolet nanoimprint lithography by means of digital holographic particle-tracking velocimetry

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ABSTRACT

There is an urgent need for micro- and nano-scale patterning methods with a high throughput and cost-effective process for the manufacture of devices of the next generation. Ultraviolet nanoimprint lithography (UV-NIL) represents a major breakthrough for next-generation lithography because of its higher resolution and greater simplicity compared with conventional technologies. However, transfer defects such as bubble defects or filling failures in the UV-NIL process have been problematic, because UV-NIL is a contact-type method. Therefore, it is important to elucidate the behavior of UV-curable resin flowing to permit control over defects in the duplicated pattern. In this study, we succeeded in measuring the flow distribution of a thin layer of UV-curable resin *in situ* during the press process of UV-NIL by means of microscale digital holographic particle-tracking velocimetry, and we clearly showed that a release agent coated onto the nanoimprint mold affects the resin flow. We believe that this study will help to provide a better understanding of the behavior of UV-NIL.

1. Introduction

Micro- and nanoscale patterning methods with a high throughput and cost-effective process are urgently needed for manufacturing devices of the next generation. Nanoimprint lithography (NIL) represents a major breakthrough in next-generation lithography because of its high resolution and its simplicity in comparison with conventional optical lithography technology [1]. In particular, the ultraviolet-NIL (UV-NIL) technique utilizes a highly sensitive photocurable resin that, theoretically, permits the implementation of high-speed pattern-transfer techniques, such as step-and-repeat processes [2] or roll-to-roll nanoimprinting [3,4]. However, some technical challenges remain to be solved from the standpoint of practical application. For example, one key problem is the lack of height of replicated pattern in comparison to the depth of the mold. Another is the presence of replication defects caused by air bubbles (bubble defects) [5]. Bubble defects are generated as a result of the retention of air in the UV-curable resin layer between the mold and the transferred substrate during the press process of nanoimprinting. In the case of the step-and-repeat process [6], the UV-curable resin is introduced onto the substrate as droplets because this is more cost-effective than spin-coating. When the droplets merge into each other, however, we have to be careful to eliminate the bubble. Therefore, optimization of the positioning of the droplets on the substrate and the resin flow are critical. Moreover, we have to consider the effects of interactions between the resin flow and release agent present on the NIL mold. To characterize these problems, it is necessary to make detailed measurements on the flow of UV-curable resin *in situ*. However, only two-dimensional (2D) information on the resin flow can be obtained by using a conventional combination of a microscope and a charge-coupled device (CCD) camera.

We previously have reported the micro-digital holographic particle-tracking velocimetry (micro-DHPTV) to measure resin flow at the curing process of UV-NIL [7,8]. However, the detailed flow behavior of the UV curable resin flow under a UV-NIL press process has not been captured. In particular, an internal flow of the UV curable resin between a mold and a transferred substrate is very important to carry out the UV-NIL. In this study, we used micro-DHPTV to measure the internal resin flow in four dimensions (x, y, z, and time) with a high resolution in a thin layer of UV-curable resin layer *in situ* during the press process of UV-NIL. We focused on the first acceleration behavior of the resin with or without the release agent in this study. As a result, the UV-resin thickness

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decreasing during the progressing NIL press process and flow distribution inside the thickness were simultaneously measured and it became clear that the release agent on the nanoimprint mold affects the resin flow near the mold substrate in the UV-NIL press process. We believe that this study will provide a better understanding of the flow behavior of UV-curable resins.

2. Experimental apparatus and procedure

Fig. 1 is a schematic depiction of our *in situ* measurement system for the UV-NIL process, which is based on the micro-DHPTV method. A Nd:YLF laser (λ = 527 nm; DS20-527, Photonics Industries International, Inc., Bohemia, NY) was used as a light source to produce a pair of laser pulses at a repetition rate of 1 kHz, a pulse length of 58 ns, and a pulse delay of 100 μs. The pressure in the UV-NIL stages was measured by means of a logger (MR8880, HIOKI E.E. Corp., Nagano). Spherical particles 2 μm in diameter (Duke Scientific R0200) were introduced into the UV-curable resin (PAK-01-CL, Toyo Gosei Co. Ltd., Tokyo) and we put a 10 μl-drop of the UV-curable resin on a substrate. Holographic images of the particles in the resin were captured by means of a CCD camera (MotionProX3, Redlake, San Diego, CA), and the coordinates of the particle were reconstructed by a digital hologram. Fig. 2 is a typical hologram captured during the press process of NIL, showing the particle fringes in a thin layer of the UV-curable resin. The CCD camera was able to capture the holographic images at 1 kHz for 3.271 s, which was adequate for measuring the velocity continuously from the start of the press process to its end. The circular pressed area was 3 cm in diameter. Fig. 3 shows a time developing distribution of the load [N] detected by the strain gage mounted under the NIL stage with the trigger timing of the shutter of the CCD camera. The shutter of the CCD camera was

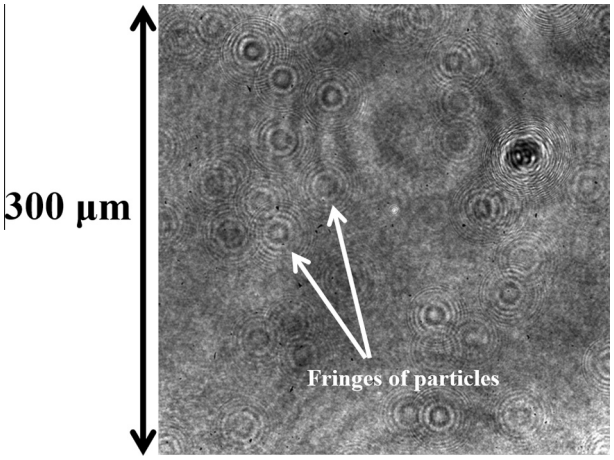

Fig. 2. Holographic image captured during press process of NIL.

automatically opened when the load reached to 10 N. The maximum load and speed of the NIL stage were set to 50 N, 10 μm/s, respectively. All the systems were synchronized by a signal generator at 1 kHz. The fringe images in x–y planes were reconstructed by FFT technique with Fresnel diffraction equation [9]. To achieve a resolution in the z position at a 1 μm-thick resin layer, the reconstruction layer between upper and lower substrates is divided into 100 sections in the z direction. After reconstruction of the coordinates, the PTV method was used to measure the velocity of the resin flow [7,8]. Averaged velocities $V(z)$ of the resin layers divided into 1 μm-thick were calculated from the sum of velocities in the x–y plane. The summarized velocity is divided by the number of obtained vectors $N(z)$ of each layer:

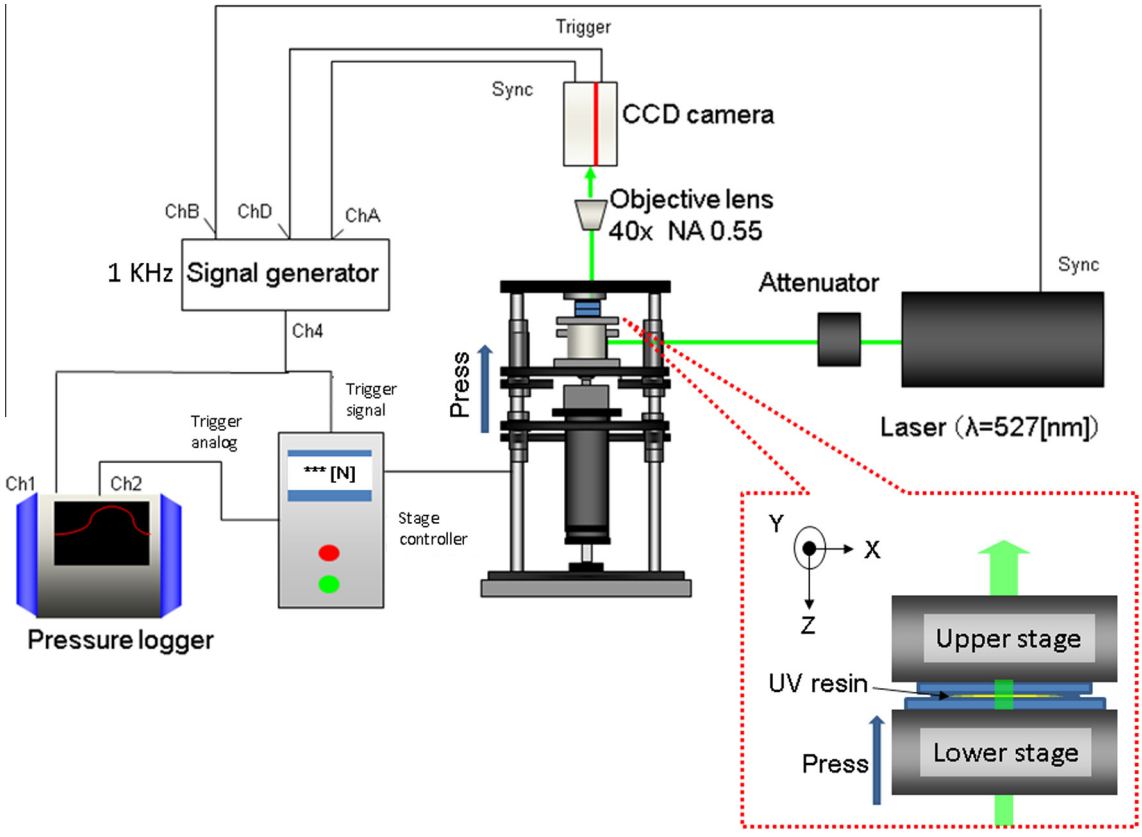

Fig. 1. Schematic view of our *in situ* measurement system.