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ORIGINAL ARTICLE

Experimental study of hybrid extrusion rolling embossing process for replicating large-area micropattern devices

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Abstract This paper reports a highly effective method for replicating large-area micropattern devices through hybrid extrusion rolling embossing using a roller mold, wherein a thin stainless steel mold with a large-area micropattern is wrapped onto a metallic roll to form a roller mold. During the hybrid extrusion rolling embossing period, the molten polymer film is extruded and immediately pressed against the embossing roller and roller mold, which results in the molten polymer completely filling the micropattern on the surface of the roller mold. Next, the molten polymer film is cooled and wound using a conveying system equipped with highly polished rollers. Thus, a continuous polymer film with many large-area micropattern devices can be fabricated. In this study, a new hybrid extrusion rolling embossing system was designed, constructed, and tested; the basic film extrusion and rolling embossing conditions were investigated; and the thickness uniformity of the polymer films and the replication quality of the micropattern devices were measured and analyzed. The results indicate that the hybrid extrusion rolling embossing can potentially be used for continuous mass production of large-area micropattern devices.

Keywords Rolling embossing · Roller mold · Micropattern

1 Introduction

Polymer micropattern devices are being increasingly utilized in various industrial applications, such as in backlight modules of TFT-LCDs, front light diffusers of LED systems, polymer microfluidic systems, biochips, and solar cell optical films. Therefore, developing an effective method of replicating polymer micropattern devices is crucial for many industrial applications. Several replication methods for the mass production of polymer micropattern devices, such as microinjection molding [1–3], hot embossing [4–6], and ultraviolet (UV) embossing [7–9], have been developed. These methods have high precision and throughput, but their efficiency is limited because they are batchwise production processes. Several concepts, such as roll-to-roll hot embossing [10–12] and roll-to-roll UV embossing [13–15], have been proposed to overcome this problem. In roll-to-roll embossing, unlike in batch production, large-area micropattern devices can be rapidly replicated on the surface of a continuous polymer film. Roll-to-roll embossing has relatively higher efficiency and lower production costs, but it has other drawbacks; for example, the employed polymer films must be purchased from commercial manufacturers and require pretreatment or preheating.

To further improve productivity, we have previously developed a hybrid extrusion rolling embossing process [16, 17] for the continuous fabrication of microlens array patterns on polymer films; in this method, which involves cast film extrusion and a roller mold, multiple micropattern devices can be directly fabricated onto a roll of polymer film in a single hybrid extrusion rolling embossing process. Only a prototype experimental facility was developed in our earlier studies, and wavelike and sharkskin defects were induced in the polymer film during the hybrid extrusion rolling embossing process. In addition, our earlier studies focused only on the fabrication of microlens arrays; the intricacies of the film extrusion and rolling embossing phenomenon remained unclear. Overall, the hybrid extrusion rolling embossing technology must be optimized before it can be commercialized.

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In this study, a new hybrid extrusion rolling embossing facility was developed in-house, and the hybrid extrusion rolling embossing with and without using a roller mold was systematically investigated. Moreover, the qualities of the polymer films and micropattern replication were measured and analyzed. Finally, the optimal molding area for fabricating large-area micropattern devices using the developed process was determined.

2 Experimental setup and method

Figure 1 is a schema of hybrid extrusion rolling embossing facility used in the experiments. The facility primarily comprises a single-screw extruder with a flat T-die, a film embossing system with an oil temperature controller, and a conveying system with highly polished rollers. The single-screw extruder is a stationary cylindrical barrel with a rotating screw inside. The barrel is often manufactured in sections and is equipped with a heating unit. The film embossing system is composed of three metallic rolls: an embossing roller (number 1), molding roller (number 2), and cooling roller (number 3). The temperature of these rollers can be controlled using the oil temperature controller. Notably, the temperature around the rollers is highly uniform, and the temperature difference on the surface of the rollers is only ± 2 °C. The embossing and molding rollers are assembled together and can be heated up to 115 °C. In this paper, the temperature and pressure of these two rollers is referred to as the rolling temperature and rolling pressure. The hybrid extrusion rolling embossing process starts by feeding plastic raw material from a hopper into the barrel of the extruder. Then, the plastic beads are melted and mixed by rotating the screw. The molten polymer travels through a flat T-die and becomes a flat film. Subsequently, the molten polymer film is embossed using the embossing and molding rollers; following which, it is cooled and wound using the conveying system and the highly polished rollers. This process yields a roll of polymer film.

In this study, an optical polycarbonate (PC) raw material (Chi Mei Corporation, Taiwan) with a glass transition temperature (Tg) of 150 °C was used for fabricating the polymer films. The width and gap of the flat T-die were 30 cm and 0.3 mm, respectively, and the temperature of the cooling roller was fixed at 50 °C. A thin stainless steel mold with a large-area micropattern was wrapped onto the molding roller to form a roller mold. After the molten polymer film was extruded, it was immediately pressed against the surface of the embossing roller and the roller mold. Consequently, the molten polymer completely filled the micropattern of the roller mold. Thus, a continuous polymer film with many large-area micropattern devices was fabricated. The T-die temperature, screw speed, rolling temperature, rolling pressure, and feeding speed could be adjusted and maintained during the experiments.

As discussed earlier, hybrid extrusion rolling embossing with and without a roller mold was investigated in this study. For the hybrid extrusion rolling embossing without a roller mold, the effects of five basic processing parameters were investigated: T-die temperature, screw speed, rolling temperature, rolling pressure, and feeding speed. To verify the feasibility and film uniformity in hybrid extrusion rolling embossing without a roller mold, the thickness of the polycarbonate film was measured at 12 measurement points each in four sections of the fabricated polycarbonate film in each experiment (Fig. 2). The thickness of the polymer film was measured using an ultrasonic thickness analyzer (45MG, Olympus). For the hybrid extrusion rolling embossing with a roller mold, a thin stainless steel mold with a microcircular hole array pattern (15 cm × 30 cm) was fabricated through photolithography and wet chemical etching [18]. The diameter, pitch, and average depth of the micropattern array were 50, 200, and 99.6 μm, respectively. The thin stainless steel mold can be wrapped, as shown in Fig. 3, to form the roller mold for replicating large-area micropattern devices.

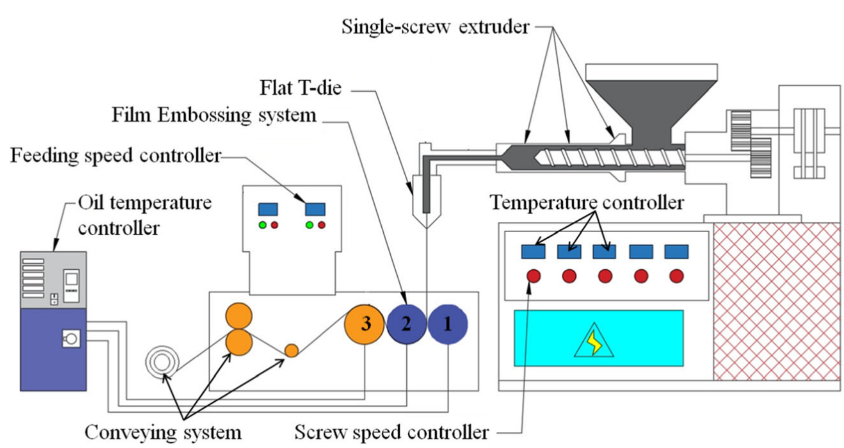

Fig. 1 Schema of the hybrid extrusion rolling embossing facility

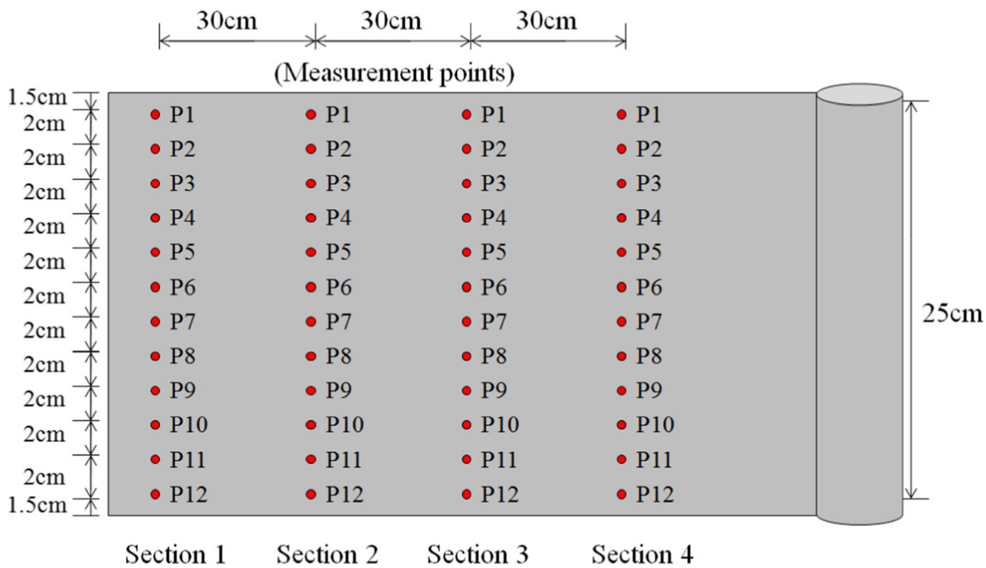

Fig. 2 Locations of the measurement points on the polycarbonate film

Replication ratio (R%) is defined as [H / D] × 100%, where H is the average height of replicated large-area micropattern device and D is the average depth of the large-area micropattern mold. In the experiments, the effects of feeding speed and rolling temperature on the replication ratio of the fabricated large-area micropattern devices were investigated. In addition, the dimensional characteristics of five large-area micropattern devices fabricated on the film were chosen and measured in each experiment; each micropattern device had nine different measure points. The shape and dimensions of the replicated micropattern device were characterized through a scanning electron microscopy (Hitachi S-3000N, Japan) and a surface profiler (Alpha-Step Profilometer, KLA-Tencor).

3 Results and discussion

3.1 Hybrid extrusion rolling embossing without a roller mold

In the preliminary experiment, hybrid extrusion rolling embossing without a roller mold was investigated. Figure 4 presents the effect of T-die temperature on the average thickness of the fabricated polymer film. In this experiment, the T-die temperature was varied from 270 to 290 °C at a screw speed of 300 rpm, rolling temperature of 90 °C, rolling pressure of 20 kg/cm^2, and feeding speed of 1.5 rpm. The results suggest that the average thickness of the fabricated polymer film decreases with an increase in T-die temperature; a

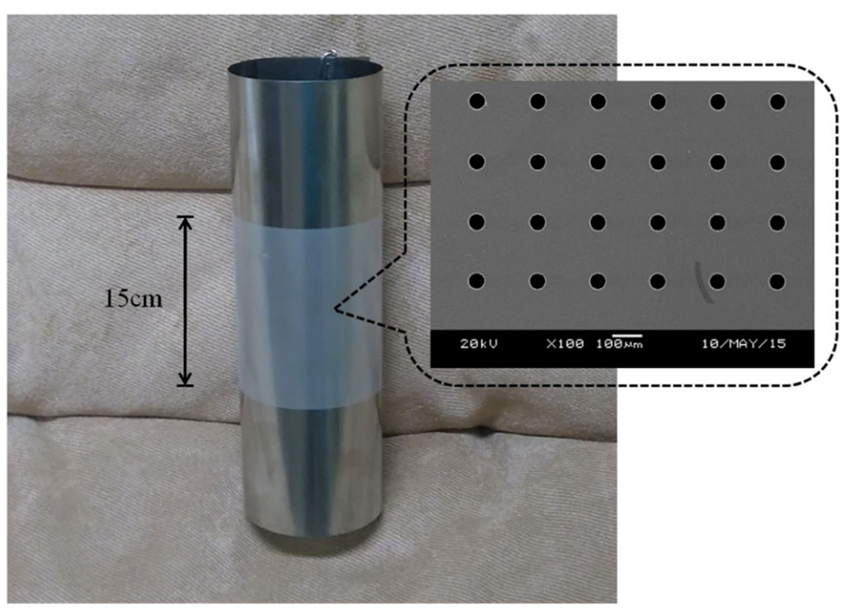

Fig. 3 Wrapped thin stainless steel mold with a microcircular hole array pattern

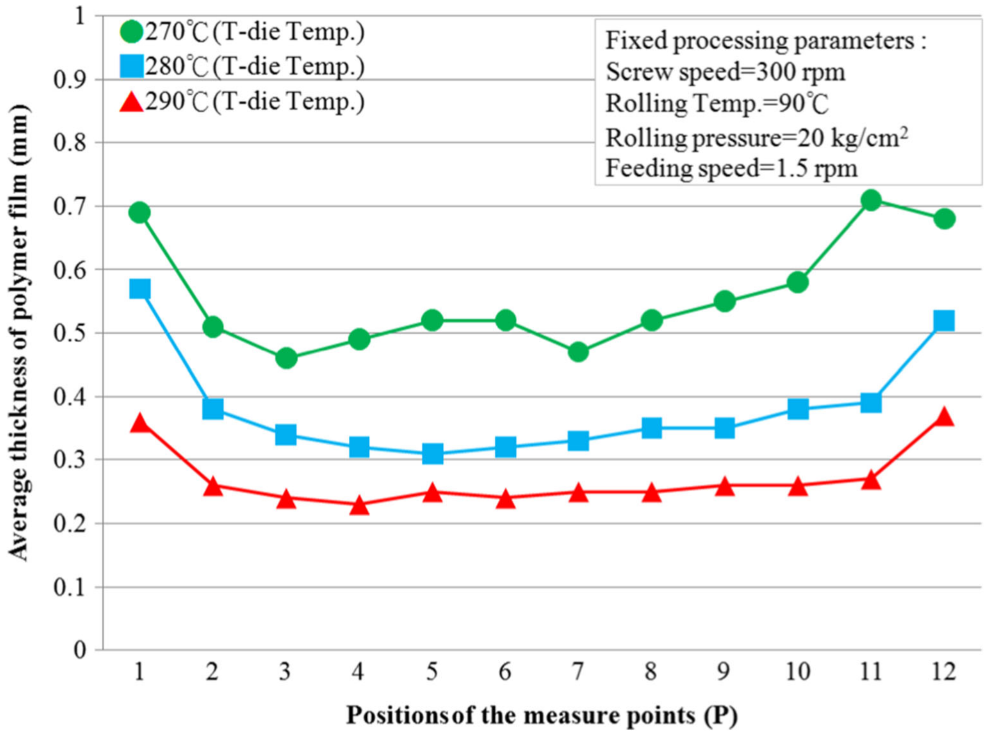

Fig. 4 Effect of T-die temperature on the average thickness of the fabricated polymer film

possible explanation is that as T-die temperature increases, the viscosity of the polymer melt decreases, and polymer neck-in and shear-thinning behaviors resulted in a decrease in the thickness of the polymer film. In addition, the edge of the film tended to be thicker than its middle. At a T-die temperature of 290 °C, the middle area of the polymer film exhibited high thickness uniformity (width of the region between P2 and P11 = approximately 18 mm). The average thickness and standard

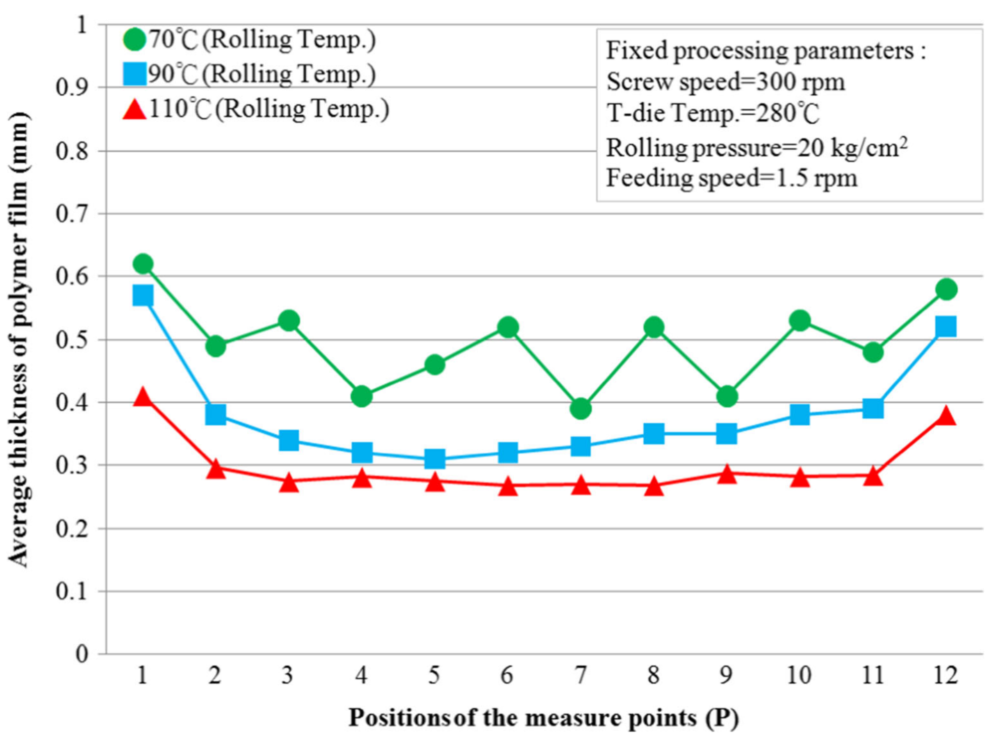

Fig. 5 Effect of rolling temperature on the average thickness of the fabricated polymer film

Fig. 6 Wavelike and sharkskin defects on the fabricated polymer film

deviation of the middle area of the polymer film was 0.27 ± 0.022 mm.

To investigate the effect of rolling temperature on the thickness of the fabricated polymer film, the rolling temperature was varied from 70 to 110 °C at a constant T-die temperature of 280 °C, rolling pressure of 20 kg/cm^2, screw speed of 300 rpm, and feeding speed of 1.5 rpm. At a rolling temperature of 70 °C, the fabricated polymer film exhibited non-uniform thickness (Fig. 5) as well as wavelike and sharkskin defects on the surface (Fig. 6). However, as the rolling temperature was increased beyond 90 °C, the surface quality and thickness uniformity of the polymer film improved and reached acceptable values.

Figure 7 presents the effect of rolling pressure on the average thickness of the fabricated polymer film. In this experiment, the rolling pressure was varied from 10 to 30 kg/cm^2 at a constant T-die temperature of 280 °C, screw speed of 300 rpm, rolling temperature of 90 °C, and feeding speed of 1.5 rpm. The results suggest that the average thickness of the fabricated polymer film decreases with an increase in rolling pressure. At a rolling pressure of 10 kg/cm^2, the rolling pressure is too low, and it will lead to insufficient embossing of the polymer film. The thickness of fabricated polymer film was thus obviously bigger and exhibited non-uniform thickness distribution. On the other hand, if the pressure is too high, it will generate residual stress in the final products and deformation of the product. In this research, the proper rolling pressure was 20 kg/cm^2.

The effect of screw speed on the thickness of the polymer film was also investigated, by varying screw speed from 200 to 400 rpm at a constant T-die temperature of 280 °C, rolling temperature at 90 °C, rolling pressure of 20 kg/cm^2, and feeding speed of 1.5 rpm. The average thickness of the fabricated polymer film increased with an increase in the screw speed (Fig. 8), because at higher speeds, the screw transfers more polymer melt from the barrel to the T-die. However, at high screw speeds, the film exhibited low surface quality and thickness uniformity, possibly because high screw speeds (polymer flow rates) induce extrusion swell behavior. This problem can

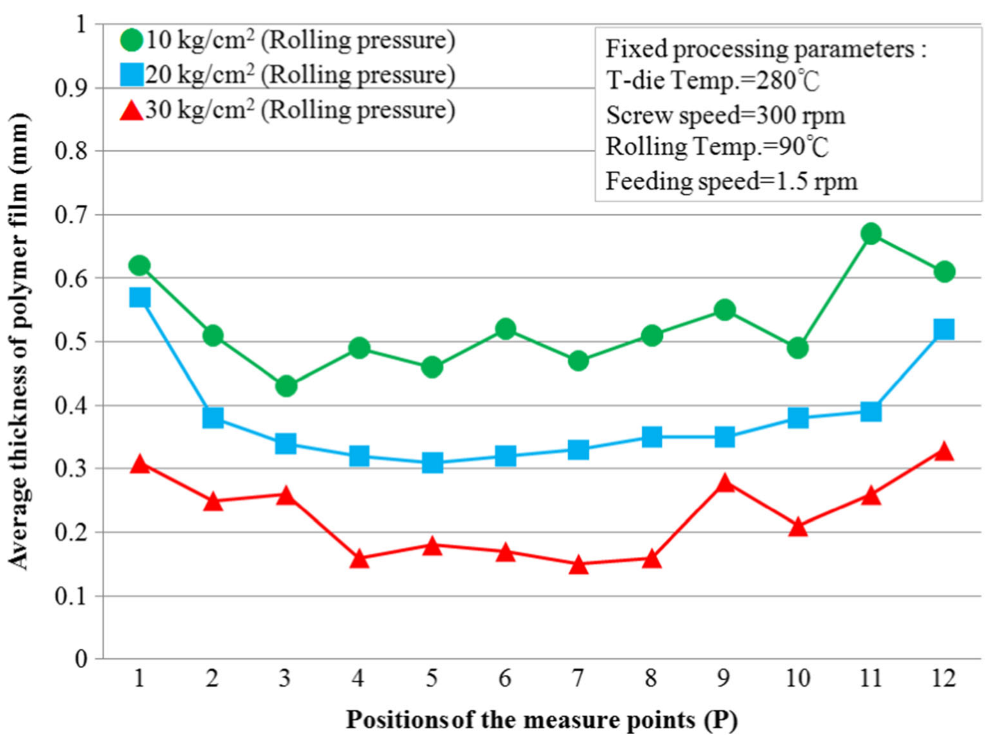

Fig. 7 Effect of rolling pressure on the average thickness of the fabricated polymer film

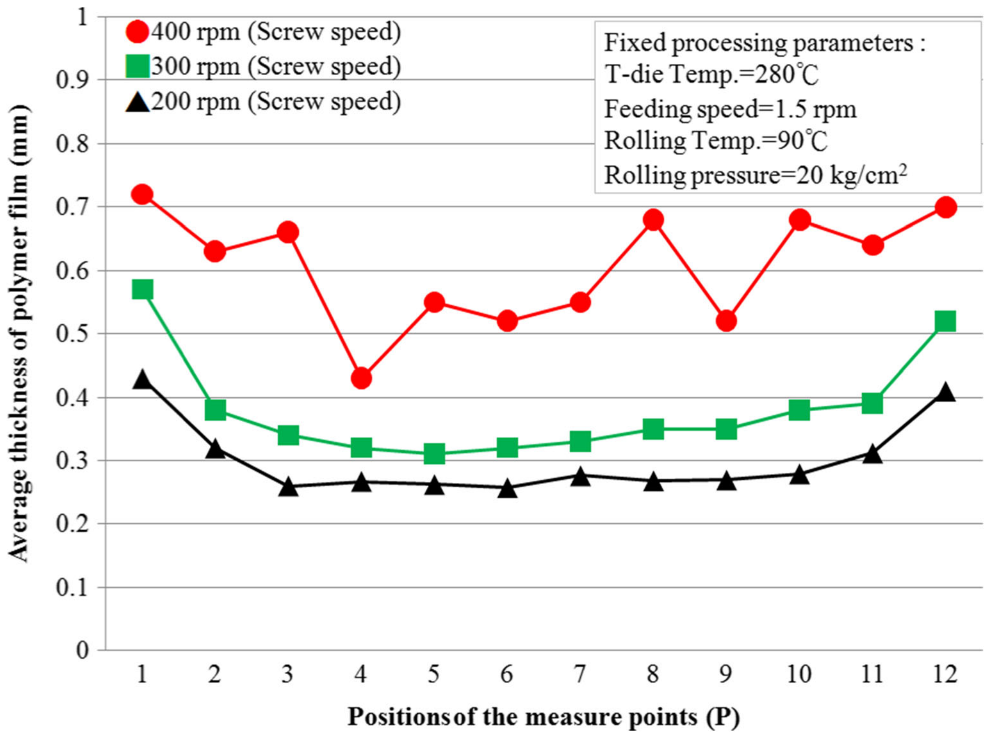

Fig. 8 Effect of screw speed on the average thickness of the fabricated polymer film

be eliminated by controlling screw speed and thus the polymer flow rate.

Next, to study the effect of feeding speed on the average thickness of the fabricated polymer film, the feeding speed was varied from 0.5 to 2.5 rpm at a constant T-die temperature of 280 °C, rolling temperature of 90 °C, rolling pressure of 20 kg/cm^2, and screw speed of 300 rpm. Increasing the feeding speed slightly decreased the average thickness of the fabricated polymer film (Fig. 9). In addition, the feeding speed did not affect the thickness uniformity of the film.

Thus, T-die temperature, rolling temperature, rolling pressure, and screw speed are the four critical processing

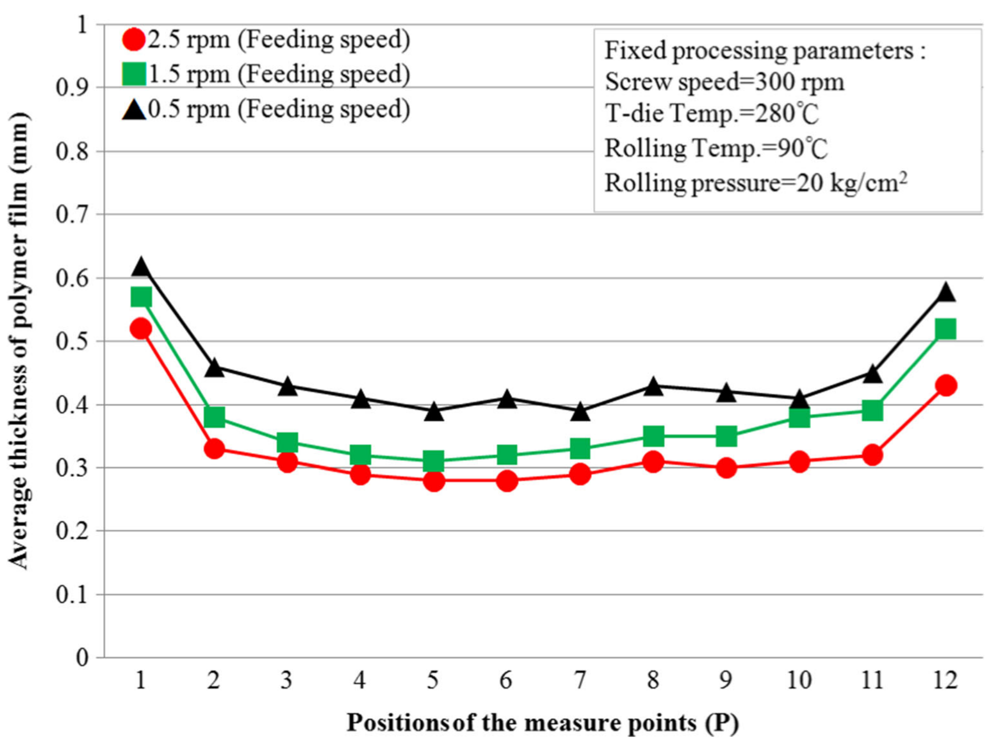

Fig. 9 Effect of feeding speed on the average thickness of the fabricated polymer film

parameters in hybrid extrusion rolling embossing without using a roller mold. The thickness of the polymer film can be adjusted by controlling the T-die temperature, rolling pressure, and screw speed, and the surface quality and thickness uniformity of the polymer film can be improved by controlling the rolling temperature. A roll of polycarbonate film with high thickness uniformity and high surface quality was fabricated under the following conditions: T-die temperature = 290 °C, rolling temperature = 90 °C–110 °C, rolling pressure = 20 kg/cm^2, screw speed = 300 rpm, and feeding speed = 0.5–2.5 rpm. The web width of the film was approximately 25 cm, and the thickness uniformity of the middle area of the film was approximately 18 mm. The surface roughness of the fabricated polycarbonate film was characterized through atomic force microscopy (AFM) on measurement points in the middle area of the polycarbonate film; the average surface roughness was 8.4 nm, and the minimum surface roughness was 8.1 nm (Fig. 10). These experimental results substantiate the feasibility of the proposed method in fabricating a roll of polycarbonate film with high surface quality that would be acceptable for many optoelectronic systems.

3.2 Hybrid extrusion rolling embossing with a roller mold

In the experiment, hybrid extrusion rolling embossing with a roller mold was implemented and investigated. To replicate the large-area micropattern devices on the polymer film with high thickness uniformity and high surface quality. The effect of feeding speed on the replication ratio of the fabricated large-area micropattern devices on the polycarbonate film was investigated by varying the feeding speed from 0.5 to 2.5 rpm at a constant T-die temperature of 290 °C, rolling temperature of 90 °C, rolling pressure of 20 kg/cm^2, and screw speed of 300 rpm. At a feeding speed of 0.5 rpm, the replication ratio of the fabricated large-area micropattern devices was 85.3% (Fig. 11). As the feeding speed was increased to 0.75–

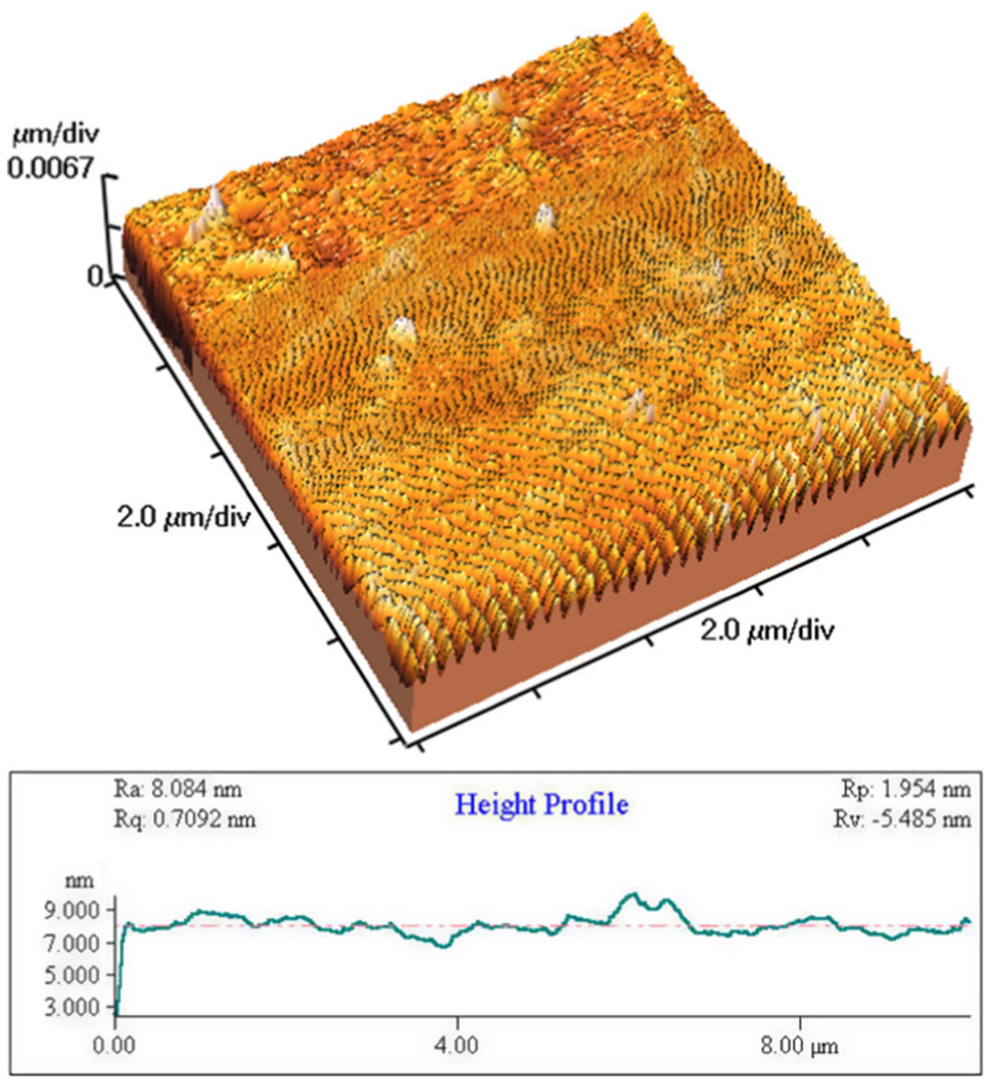

Fig. 10 AFM image and roughness analysis of the fabricated polymer film

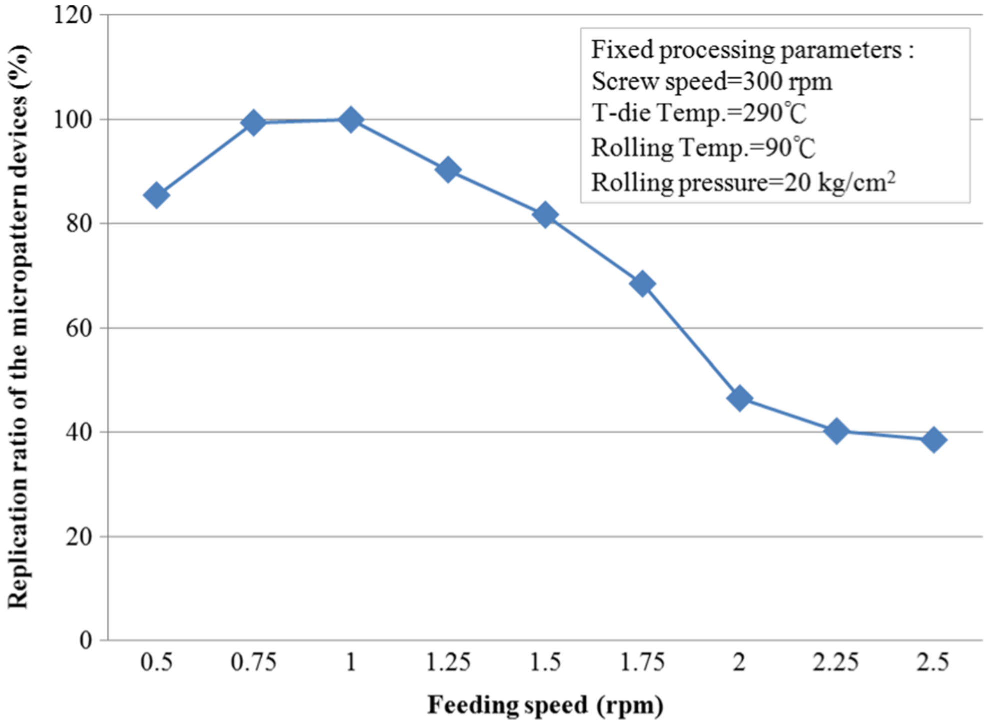

Fig. 11 Effect of feeding speed on the replication ratio of the fabricated micropattern devices

1 rpm, the replication ratio of the fabricated devices reached 99–100%, indicating that the polymer melt completely filled the microcircular hole array of the mold and formed a complete cylinder array pattern on the polycarbonate film. However, with further increases to the feeding speed, the replication ratio of the fabricated devices decreased rapidly, suggesting that the average height of the replicated micropattern structures decreases with an increase in the feeding speed. In addition, the shape of the micropattern structures changed from a cylinder to a hemisphere, possibly because the contact time between the polymer melt and the roller mold decreases with an increase in the feeding speed; in other

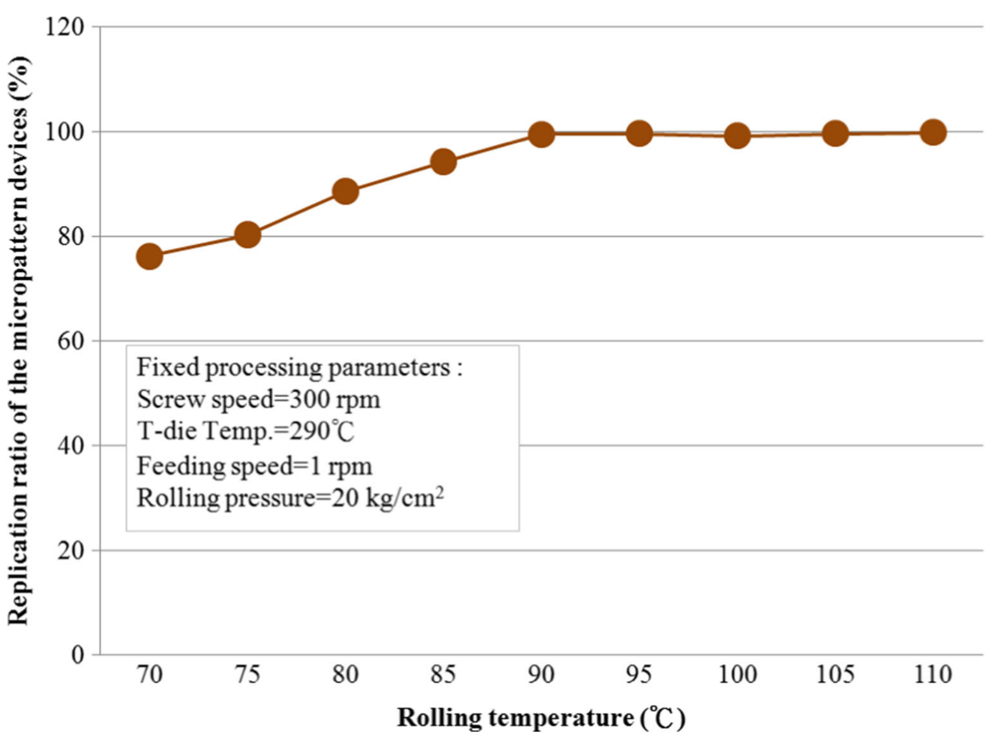

Fig. 12 Effect of rolling temperature on the replication ratio of the fabricated micropattern devices

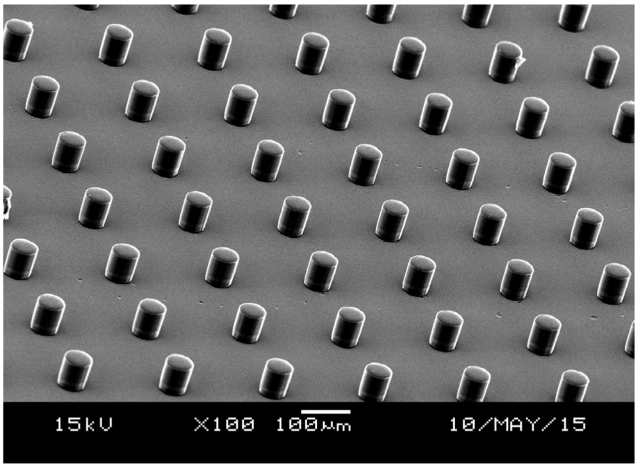

Fig. 13 Microcylinder array pattern on the polycarbonate film

words, at a high feeding speed, the molten polymer material does not have sufficient time to flow and fill the microcircular hole array of the roller mold.

Figure 12 presents the effect of rolling temperature on the replication ratio of the fabricated large-area micropattern devices. The replication ratio of the devices gradually increased with an increase in the rolling temperature. When the rolling temperature exceeded 90 °C, the replication ratio reached 99–100%.

Thus, the molding area of the proposed process can be optimized by controlling two key processing parameters: feeding speed and rolling temperature. At a T-die temperature 290 °C, rolling pressure of 20 kg/cm^2, and screw speed of 300 rpm, the optimal feeding speed and rolling temperature ranges are 0.75–1 rpm and 90–110 °C, respectively. Under these conditions, a polycarbonate film with high thickness uniformity and high surface quality can be obtained, and the replication ratio of the fabricated micropattern devices in the optimal molding area becomes 99–100%, yielding a roll of polycarbonate film with microcylinder array patterns (Fig. 13). Outside the optimal molding area, the replication ratio of the fabricated micropattern devices is less than 99–100%, and a microhemispherical array or incomplete filling patterns can be observed on the film (Fig. 14).

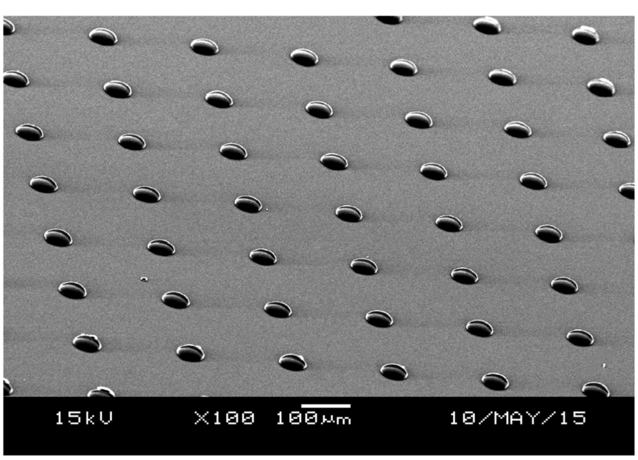

Fig. 14 Microhemisphere array and incomplete filling pattern on the polycarbonate film

4 Conclusions

An effective method for replicating large-area micropattern devices through hybrid extrusion rolling embossing was reported and demonstrated. Under proper processing conditions, a roll of polycarbonate film with high thickness uniformity in the middle area was successfully fabricated. This polycarbonate film had acceptable surface quality. Furthermore, a thin stainless steel mold with a large-area micropattern was wrapped onto the molding roller to form a roller mold, and a continuous polymer film with many large-area micropattern devices was successfully replicated. Under the following conditions: T-die temperature = 290 °C, rolling pressure = 20 kg/cm^2, and screw speed = 300 rpm, the optimal range of feeding speed and rolling temperature were determined as 0.75–1 rpm and 90–110 °C, respectively. The replication ratio of fabricated micropattern devices reached 99–100%. These experimental results evidence that the proposed method can replicate large-area micropattern devices with high precision, high productivity, and low cost.

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References

1. Su YC, Shah J, Lin LW (2004) Implementation and analysis of polymeric microstructure replication by micro-injection molding. J Micromech Microeng 14:415–422
2. Shen YK, Chang CY, Shen YS, Hsu SC, Wu MW (2008) Analysis for microstructure of microlens arrays on micro-injection molding by numerical simulation. International Communications in Heat and Mass Transfer 35:723–727
3. Zhang N, Chu JS, Byrne CJ, Browne DJ, Gilchrist MD (2012) Replication of micro/nano-scale features by micro injection molding with a bulk metallic glass mold insert. J Micromech Microeng 22:065019
4. Kimerling TE, Liu W, Kim BH, Yao D (2006) Rapid hot embossing of polymer microfeatures. Microsyst Technol 12:730–735
5. Kuo CC, Hsu HJ (2013) Micro-hot embossing of Fresnel lens using precision micro-featured mold. Mater Manuf Process 28:1228–1233
6. Lin MC, Yeh JP, Chen SC, Chien RD, Hsu CL (2013) Study on the replication accuracy of polymer hot embossed microchannels. International Communications in Heat and Mass Transfer 42:55–61
7. Chan-Park MB, Neo WK (2003) Ultraviolet embossing for patterning high aspect ratio polymeric microstructures. Microsyst Technol 9:501–506

8. Huang PH, Huang TC, Sun YT, Yang SY (2008) Fabrication of large area resin microlens arrays using gas-assisted ultraviolet embossing. Opt Express 16(5):3041–3048
9. Chen JW, Cheng J, Zhang D, Chen SC (2016) Precision UV imprinting system for parallel fabrication of large-area micro-lens arrays on non-planar surfaces. Precis Eng 44:70–74
10. Yeo LP, Ng SH, Wang ZF, Wang ZP, Frans de Rooij N (2009) Micro-fabrication of polymeric devices using hot roller embossing. Microelectron Eng 86:933–936
11. Velten T, Bauerfeld F, Schuck H, Scherbaum S, Landesberger C, Bock K (2011) Roll-to-roll hot embossing of microstructures. Microsyst Technol 17:619–627
12. Yi P, Shu Y, Deng Y, Peng L, Lai X (2015) Mechanism of forming defects in roll-to-roll hot embossing of micro-pyramid arrays I: experiments. J Micromech Microeng 25:105017
13. J. Taniguchi, H. Yoshikawa, G. Tazaki, T. Zento, High-density pattern transfer via roll-to-roll ultraviolet nanoimprint lithography using replica mold, Journal of Vacuum Science & Technology B 30 (2012) 06FB07
14. Yoshikawa H, Taniguchi J, Tazaki G, Zento T (2013) Fabrication of high-aspect-ratio pattern via high throughput roll-to-roll ultraviolet nanoimprint lithography. Microelectron Eng 112:273–277
15. Zhong ZW, Shan XC (2014) A study of meniscus formation and its effect on roll-to-roll UV embossing. Int J Eng Sci 85:10–19
16. Jiang LT, Huang TC, Chiu CR, Chang CY, Yang SY (2007) Fabrication of plastic microlens arrays using hybrid extrusion rolling embossing with a metallic cylinder mold fabricated using dry film resist. Opt Express 15(19):12088–12094
17. Chang CY, Tsai MH (2015) Development of a continuous roll-to-roll processing system for mass production of plastic optical film. J Micromech Microeng 25(12):125014
18. Chang CY, Chu JH (2017) Innovative design of reel-to-reel hot embossing system for production of plastic microlens array films. Int J Adv Manuf Technol 89:2411–2420