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Continuous roll-to-flat thermal imprinting process for large-area micro-pattern replication on polymer substrate

Shuhuai Lan [a,b], Jung-Han Song [b], Moon G. Lee [c], Jun Ni [d], Nak Kyu Lee [b], Hye-Jin Lee [b,*]

[a] Department of Mechanical Engineering, Shanghai Jiao Tong University, Shanghai, People's Republic of China
[b] Department of Manufacturing Convergence Technology, Korea Institute of Industrial Technology, Ansan, Republic of Korea
[c] Division of Mechanical Engineering, Ajou University, Suwon, Republic of Korea
[d] S.M. Wu Manufacturing Research Center, University of Michigan, Ann Arbor, MI 48109, USA

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ABSTRACT

Conventional imprinting process in flat-pressing mode meets with the problem of limited efficiency as a discontinuous batch-wise process in many new applications that demand micro-/nano pattern replication over large area with low cost and high throughout in mass production manufacturing. To overcome such problem, alternative imprinting process in a continuous roller-pressing mode has been gaining more attention since it has many advantages. However, few studies have been reported on the investigation of filling mechanism in roller-pressing type imprinting process. In order to have a better understanding of polymer flow behavior in roller-pressing type imprinting process, it is necessary to establish a criterion of evaluation for roller-pressing type imprinting process. In this paper, an analytical model for the cavity-filling of polymer flow in roll-to-flat (R2F) imprinting process is derived based on Hertz contact pressure distribution and Navier–Stokes equation. The feasibility of the model is evaluated using a lab-scaled prototype of a R2F micro thermal imprint system for micro-pattern replication over large area on polymer substrate. Series of tests are conducted to investigate the effects of process control parameters on the replication ratio. In results, there is good agreement between the model prediction and experiments when pattern replication is examined according to the change of control parameters such as rolling speed and loading pressure.

1. Introduction

In micro-/nano-fabrication area, imprinting process has been developed and researched as one of the most popular replication technologies since the last decade because it takes the advantages of low cost, simple operation, high throughput and relatively higher resolution [1–3]. In the research fields such as biomedicine, life science, optoelectronics and solar cell, many new applications have been promoted [4–6]. In the development of this replication technology, one of the key issues is the replication area since it directly relative with the throughput and efficiency of the process. As the requirement increases, there is more demand on reducing the manufacturing cost, increasing the process efficiency and realizing the mass production. For new applications such as flexible display, e-paper, flexible solar cell and polymeric microfluidic devices and so on, the size of product is larger and larger. The replication area in the process is usually from tens of square centimeters to several square meters. Conventional imprinting process in flat-pressing mode as a discontinuous batch-wise process faces the problems of limited efficiency, nonuniformity, low throughput, small replication area, etc.

In order to overcome the problems, continuous imprinting process with roller (or flat) mold and roller-pressing has been highlighted since it has the advantages of better uniformity, less loading pressure, simple structure, high efficiency and low cost. This is because it is basically continuous fabrication process while the conventional flat-pressing type imprinting process is discontinuous. Especially for the large-area micro-pattern replication, roller-pressing imprinting process has been demonstrated as a competitive technology.

Continuous roller-pressing process such as roll-to-roll (R2R, roller mold + roller-pressing) or roll-to-flat (R2F, flat mold + roller-pressing), has been currently applied in some industrial fields, such as gravure printing or flexography printing (or flexo). It is used to imprint intended patten on flexible thin films continuously. The replicated pattern is transferred from the roller mold or flat mold onto the surface of substrate. In the field of micro-/nano-fabrication, Chou group firstly proposed the combination of imprinting and roller-pressing and then developed roller nanoimprint lithography (RNIL) process for rapid pattern replication on a large area substrate [7]. Such RNIL process provides advantages

* Corresponding author. Tel.: +82 31 8040 6824; fax: +82 31 8040 6820.
E-mail address: naltl@kitech.re.kr (H.-J. Lee).

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such as simple equipment, lower imprint force, better replication uniformity because only a line area is in contact during imprinting. Particularly in the field of manufacturing for flexible electronics, the fabrication method via R2R processes have been demonstrated by some researchers. For example, Wang Xiaojia et al. have developed a novel full color electrophoretic film manufacturing process using roller-pressing method [8]. S.C. Liang group developed a continuous process using R2R method combining all process steps including: polymer coating, pattern embossing, filling/sealing, and lamination for manufacturing of flexible display or electronic paper at a low cost and high speed [9–11].

However, the continuous roller-pressing imprinting process for the fabrication of micro-pattern on the polymer substrate has not been investigated adequately and most of them are based on ultraviolet-curing techniques. For the thermal continuous imprinting process, most of investigations focus on the system development and experimental study. Few studies have been reported the filling mechanism in roller-pressing type imprinting process. In order to have a better understanding of polymer material flow behavior in the roller-pressing type imprinting process, it is necessary to establish a criterion of evaluation for roller-pressing type imprinting process.

In this study we aim to develop an analytical model for the cavity-filling of polymer flow in roll-to-flat (R2F) imprinting process, which is derived based on Hertz contact pressure distribution and Navier–Stokes equation. Our goal is to obtain a relationship between process control parameters and process result. Based on a lab-scaled prototype of a R2F micro thermal imprint system, the feasibility of the model is evaluated for the micro-pattern replication over large area on polymer substrate. Series of tests were conducted to investigate the effects of process control parameters, i.e. rolling speed and loading pressure on the replication ratio on polycarbonate (PC) substrate.

2. Analytical model of polymer flow behavior

In the conventional flat-pressing type imprinting process, the loading pressure between mold and substrate is usually regarded as constantly static and uniform. However, as shown in the Fig. 1a, in the R2F imprinting process, under the pressing of roller, the pressure distribution is the function of distance to the central contact point. In one dimension and for slow rolling, according to Hertz contact solution, the pressure distribution is given by:

$$P(x) = \frac{8F}{\pi a^2 L}\left[\left(\frac{a}{2}\right)^2 - x^2\right]^{1/2} \tag{1}$$

where $P(x)$ is the pressure distribution, F is the normal applied force, a is the contact length and L is width of the roller as well as the flat mold [12].

For every small mold cavity in the contact area, the rolling motion of roller is equivalent with the motion which the roller is fixed (only rotating with its center axis) while the flat mold moves forward, as shown in Fig. 1b. Noting t_c as one contact time cycle, then t_c is expressed as: $t_c = a/v$, where v is the moving speed of flat mold, which is also the web speed of the roller. As presented in Eq. (1), therefore, the pressure distribution applied on every mold cavity can be expressed as function of time as the roller rolling forward in the contact area:

$$P(t) = \frac{8F}{\pi a^2 L}\left[\left(\frac{a}{2}\right)^2 - \left(-\frac{a}{2} + vt\right)^2\right]^{1/2} (0 \leqslant t \leqslant t_c) \tag{2}$$

Since the roller and flat mold width L is much larger than contact length a, the material flow in y-direction can be neglected. On the other hand, since the substrate thickness is relatively much larger than the depth of mold cavity, it is assumed that there is only the material flow in z-direction to fill the mold cavity. Then the analytical model of material flow behavior is established, as shown in Fig. 2. H is the cavity depth, w is the cavity width. The primary driving force moving the polymer into the cavity is the pressure difference created by the roller during roller-pressing imprinting [13].

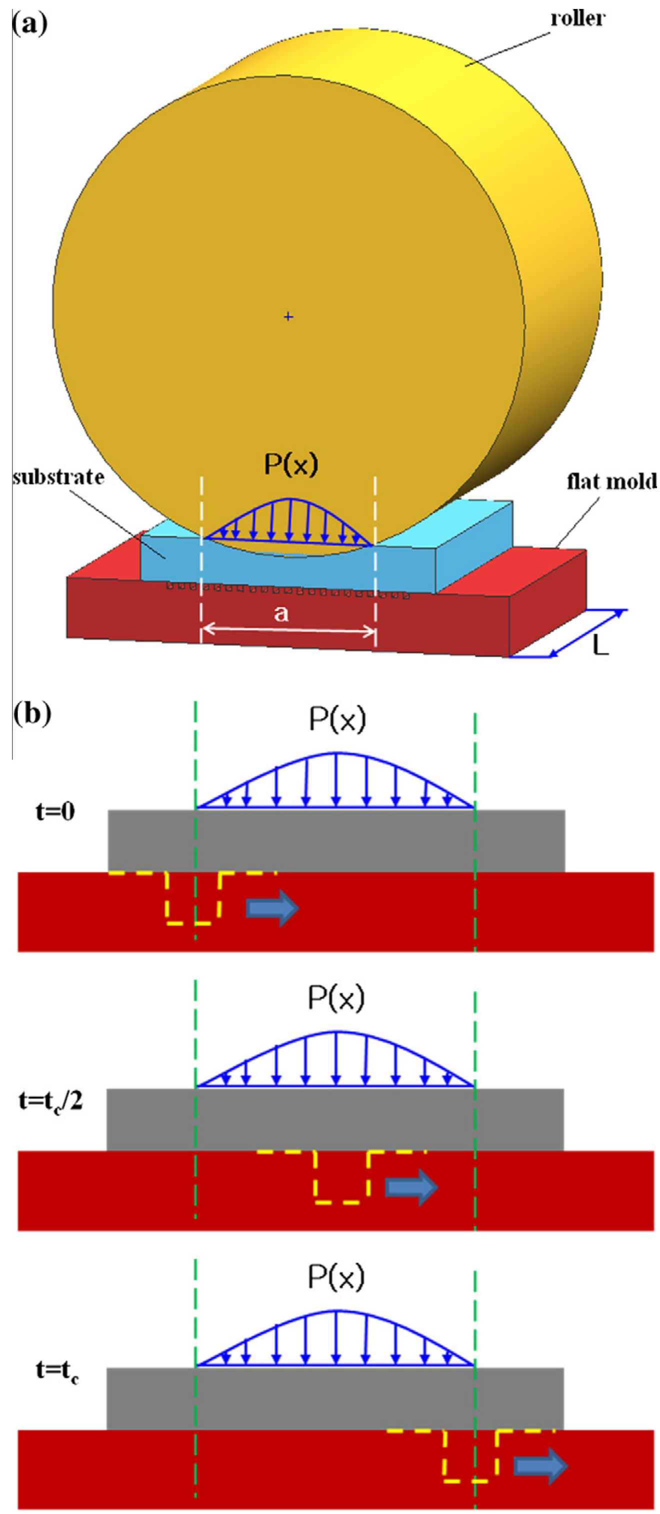

Fig. 1. Schematic diagram of the contact model in the R2F imprinting process: (a) geometrical configuration and (b) pressure distribution as function of time.