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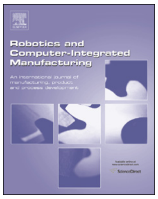

# Statistical analysis for the manufacturing of multi-strip patterns by roll-to-roll single slot-die systems

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ABSTRACT

Roll-to-roll (R2R) slot-die coating systems are mostly devoted to the mass manufacture of printed electronics. This study examined the correlation among the operating conditions, thickness, and width of the patterned strip fabricated by the R2R slot-die system. A full factorial experiment was conducted to screen for effective parameters. The velocity of a moving substrate was found to be the most dominant parameter affecting the thickness and width of the patterned strips. The flow ratio of the supply to the slot-die, and gap between substrate and slot-die did not affect the width of the strip, but affected the thickness; therefore, the flow ratio and gap can be employed for the independent patterning of thickness against width. In addition, it was proposed to determine the R2R process conditions, such as gap, velocity, and flow ratio for the desired thickness and width of the patterned strips.

## 1. Introduction

The roll-to-roll (R2R) printing methodology using gravure, inkjet, and slot-die printing technologies has been adapted for the manufacturing of printed electronic devices such as printed sensors, RFID tag, rectifier, OPV, EMI filter, artificial skins, etc. [1–8]. Mass production is desirable to open additional markets for "ambient intelligence" by R2R printed electronics for reducing the product cost [9].

Slot-die is one of the most promising technologies for the manufacturing of printed electronics which are multi-layered and flexible, and the ability of the slot-die method to produce pre-metered, thin, uniform, and large-area printing has made it the target of recent research [10]. Blankenburg proposed upscaling the process for thin polymer solar cells (OPV) using a laboratory R2R slot-die printing machine [11]. Krebs proposed polymer solar cell modules manufactured by full R2R processing (comprising flexography, slot-die, and rotary screen printing), which have a best power conversion efficiency of 2.75%. He also proposed the use of slot-die printing and screen printing for an indium tin oxide (ITO)-free flexible polymer solar cell with an efficiency of 1.4% [12,13]. Galagan analyzed the effect of process conditions on the performance of polymer solar cells that were adjusted for slot-die R2R printing [14].

In the slot-die printing, the thickness of printed pattern is determined in advance of the experiment by adjusting the flow rate of the solution that supplied to the slot-die according to the operating velocity of the moving substrate. It is known that the velocity of the moving substrate, the capillary number, and the viscosity of solution determine the thickness. However, the determination of the thickness is valid only by the applying of slot-die for whole coating or single strip printing due to its limitation of 2-dimensional mathematical model [15].

When the slot-die is applied in a multi-strip printing rather than to the whole area coating or single-strip printing, it is important to control the width of the patterned strip as well as the thickness precisely. In multi-layered printed circuits, printing errors with regard to the width of the strip can generate short-circuits or electricity leakages.

There have been several studies on the influence of the process conditions of the slot-die, including the velocity, the thickness of the coated layer, the flow rate of the solution supplied to the slot-die, and the viscosity of the solution. Romero analyzed the mechanism of the limit of minimum thickness at given conditions of substrate velocity, capillary, and inertial forces in the flow [10,16]. Lin carried out theoretically two-dimensional numerical estimations on the operating windows of the slot die [17]. Chang investigated the minimum wet thickness of the slot-die coating in

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experimental studies [18]. All of these results were carried out in a two-dimensional plane which consists of thickness-axis and time-axis, under the typical assumption of no variation in the width of the slot-die coated pattern. However, the width of the patterned strip is also subject to the operating conditions, which affects the quality of registration in multilayered patterning [13,14]. Accordingly, it is important to analyze the correlation between the process parameters and the coated thickness and width of the multi-strip. However, there has been no research with regard to variations in the width of the slot-die patterned multi-strip with changes in process conditions. In the current study, the effects of the operation parameters on the thickness and the width of the strips were analyzed. Using the full factorial design of experiment, the effects of operating conditions were examined in the range of experimental inputs. Analysis of Variance (ANOVA) tool was employed for statistical analysis of the major parameters. In addition, a mandatory strategy was proposed for fabricating multi-strip with the desired thickness and width by single slot-die system. These results can be used to tune the operating conditions for the patterning of multi-strip by the R2R slot-die systems (Fig. 1).

## 2. Mathematical modeling

The typical cross sectional view of slot-die lip during the coating process is depicted as shown in Fig. 2. At the downstream, the maximum pressure difference is calculated as Eq. (1) in given conditions of surface tension and gap between slot-die lip and substrate by the viscocapillary model [19].

$$\Delta P_{max} = \frac{2\sigma}{H_0 - t} \tag{1}$$

where $\sigma$ is surface tension, $H_0$ is gap between slot-die lip and substrate, $t$ is thickness of coated layer.

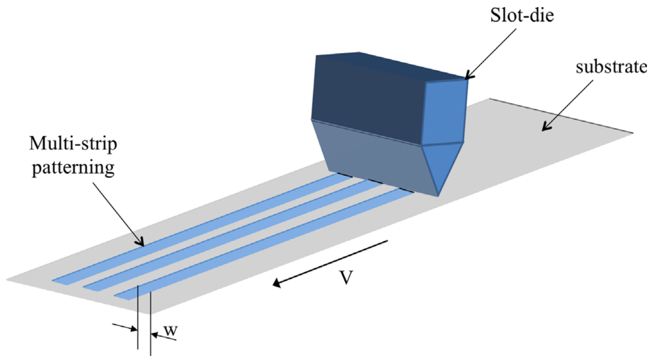

**Fig. 1.** Multi-strip patterning using single slot-die system.

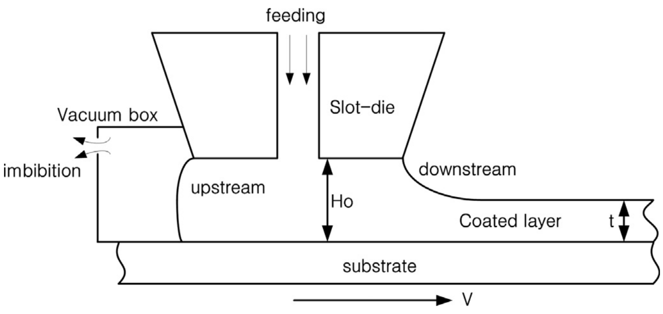

**Fig. 2.** Schematic of slot-die lip during coating process.

Also, Landau and Levich [20] suggested the pressure drop along the meniscus of downstream as follows:

$$\Delta P_{max} = 1.34\mathrm{Ca}^{2/3}\frac{\sigma}{t} \tag{2}$$

where Ca is capillary number.

The capillary number is defined as

$$\mathrm{Ca} = \frac{\mu V}{\sigma} \tag{3}$$

where $\mu$ is viscosity, $V$ is the velocity of a moving substrate.

The minimum thickness of the coated layer using the slot-die printing system can be determined as the following equation by combining Eqs. (1)–(3):

$$t_{min} = \frac{H_0}{1 + 1.49(\mu V/\sigma)^{-2/3}} \tag{4}$$

Eq. (4) physically means the minimum thickness of coated layer, which do not break up the meniscus between slot die and substrate. In Fig. 3 effects of operating parameters on the minimum thickness were depicted as a function of velocity, viscosity, and gap. The operating condition was velocity of 7 m/min, viscosity of 4 mPa s, and surface tension of 20 dyn/cm. In both Fig. 3(a) and (b), the minimum thickness was proportional to the gap between slot-die and substrate. Also velocity and viscosity were proportional to the minimum thickness. Besides, the effect of velocity and viscosity on the thickness was increased as the size of gap raised.

In experiment, however, the thickness of coated layer could be larger than minimum thickness due to the flow rate of feeding solution, which was not considered in Eq. (4). In addition, from the experimental studies by Lee and Liu [21] the minimum thickness can be achieved only using negative pressure in the vacuum box of Fig. 2. It is known that without the negative pressure the thickness is greater than the minimum thickness of Eq. (4). Normally ambient printing condition is required for the wide applicability in the R2R printing process. In the general R2R printing condition of no vacuum box, therefore the minimum thickness of printed layer is greater than the results of Eq. (4).

Applying the law of conservation of mass to the slot-die nozzle in Fig. 2, it yields the following equation:

$$\frac{d}{dt}\int V(x)dx = f_r - [nwtV] \tag{5}$$

where $V(x)$ is mass in control volume, $f_r$ is flow rate of supplying solution, $n$ is number of strips, $w$ is width of strip, $t$ is thickness of strip, $V$ is operating velocity.

At the steady-state Eq. (5) can be written as

$$f_r = nwtV \tag{6}$$

Combining and rearranging Eqs. (4) and (6) give

$$w = \frac{f_r}{nVH_0}\left[1 + 1.49\left(\frac{\mu V}{\sigma}\right)^{-2/3}\right] \tag{7}$$

Eq. (7) is the width of the strip for minimum thickness of coated layer by the slot-die. As it was mentioned before, the thickness in experiment could be higher than Eq. (4) of minimum thickness due to no consideration of flow ratio. So, Eq. (7) of the width should also be affected by the variation of coated thickness. Therefore, experimental studies were performed to investigate the effects of operating parameters including flow ratio, velocity, and gap on the thickness and width of printed patterns.