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Optimized design for anti-reflection coating process in roll-to-roll slot-die coating system

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ABSTRACT

This study investigated the application of the anti-reflection (AR) coating technology by using the roll-to-roll (R2R) slot-die coating process. To simulate the coating phenomenon, we investigated governing parameters in the slot-die coating process by using a viscocapillary model. Results of using this model revealed that the coating speed and solid content are two dominant factors affecting transmittance, which is an important parameter for the AR coating process. As the design of experiment methodology, response surface design was used to observe parameter interactions and establish a meta model for obtaining optimum process conditions. Further, to enhance the accuracy of analysis of the coating performance, the light wavelength was divided into visible and IR wavelength regions. In addition, the average and standard deviation values of transmittance were determined by a statistical correlation. An improvement of approximately 5% of the transmittance was observed in comparison to that of an uncoated (bare) substrate. The optimum conditions of process parameters for the AR coating process were determined through the established meta model and guidelines for performing the AR slot-die coating process were suggested.

1. Introduction

Recent studies [1–3] have revealed a shifting trend toward the use of organic photovoltaic (OPV) cells in products in the near future on account of the drawbacks of conventional copper indium gallium selenide (CIGS) and cadmium telluride (CdTe) solar cells, in that they require a chemical etching process, which contaminates the environment and increases the product cost. OPV cells are instead preferred because they can be feasibly fabricated by using the roll-to-roll (R2R) process, which has several advantages, such as being inexpensive, environmentally friendly, and commercially feasible, and enabling mass production [4–6].

However, OPV cells still have a few drawbacks, e.g., a low power conversion efficiency and instability. Nevertheless, OPV cells can be manufactured with high productivity. Recently, research has been conducted on the lab-scale production of OPV cells using the R2R process, with the highest efficiency achieved being 8% [7,8]; however, the reliability and lifetime of such OPV cells are lower than those of silicon-based solar cells. In this study, we focus on improving light collection, which would guarantee the stability of OPV cells. In particular, we attempt to improve the performance of the anti-reflection (AR) coating, which will in turn increase their transmittance and thus their external quantum efficiency (EQE) of OPVs. This improvement could partially affect the power conversion efficiency (PCE) of OPV cells [9–12].

Through AR coating technology, the reflectivity of OPV cells can be reduced by coating a specific substance on the surface of the substrate during the coating process. The AR coating process, which is an alternative approach for fabricating a protective film on OPV cells, plays a role in potentially improving the performance of mass-produced solar cells [13,14]. The AR coating layer can substantially reduce the glare and glitter on optical instruments and flat panel displays because it reduces the amount of reflected light. AR coating on films can be achieved by several approaches. For example, Hiller et al. succeeded in performing AR patterning on films by using an inkjet printing technique; this method is potentially useful for pH-responsive biomaterials and membrane applications [15]. Furthermore, several techniques are available for applying an AR coating on a flexible substrate, such as gravure coating, spin coating, and spray coating [16–18]; however, the slot-die coating technique is preferred over such coating techniques because it can be applied to the R2R process in a noncontact manner.

Slot-die coating, also called premetered coating, is a well-known technique that can be used to estimate layer thickness by using process variables. For obtaining a good-quality coating, reliable process conditions must be set, which are presented as a

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coating window. This concept is well described by the viscocapillary model and experimental verification [19–21]. The viscocapillary model explains the effect of surface tension force in the upstream and downstream menisci, but numerical analysis is more accurate for confirming the viscous stress and inertia force in the non-Newtonian flow of the coating [22,23].

A previous work has investigated the slot-die coating of polyvinyl alcohol solution containing inorganic particles [24]. In that study, a numerical simulation was performed by using commercially available 3-D flow software, and SiO_2 was used for the analysis. In the present study, SiO_2 diluted with isopropyl alcohol was used for the AR coating process using R2R processing. Fig. 1 shows a scanning electron microscope (SEM) image of an AR surface dip-coated with the abovementioned solution containing SiO_2 nanoparticles. The solution used in this experiment is possible to fabricate with various solid content for the slot-die coating process. Here, it is important to choose an appropriate solid content that would give optimum surface characteristics such as the thickness and uniformity of the coated surface. Further, the coating performance, which is directly affected by process parameters such as particle size, solid content, and curing degree, plays a very crucial role in the transmittance performance of an optical device. Specifically, the coating layer is dried by the R2R system through a continuous web transport process. The drying time of the coating solution should therefore be considered an important characteristic affecting coating performance.

In the R2R process, before the flexible substrate is transformed into the final product, it must travel from the unwinder to the rewinder and then pass through several idle rollers, tension controllers, and drying units, as shown in Fig. 2 [25]. Therefore, the coating layer on the substrate must be maintained without shaking, and the curing period must be consistent with the specifications of the final product. Thus, web handling techniques are considered essential elements for guaranteeing the stability and performance of the coating layer in the slot-die coating zone [26,27].

In this study, we propose optimization of the AR coating process based on experimental results, with the aim of making it more feasible for mass production. To the best of our knowledge, no study has yet reported AR slot-die coating using the R2R process; furthermore, it is important to take into account several process conditions for ensuring high performance of the final product. In this study, a simulation was performed using a viscocapillary model to predict the experimental results in terms of thickness, and the simulation results were in turn verified by experiments performed on the R2R system. This study also aimed to establish a mathematical model for the AR coating layer, which is expected to be useful for optimizing the parameters that affect the performance of the final product through the performance of the layer. The transmittance of the AR-coated layer, rather than its thickness, was analyzed to derive the required process conditions in the case of using the R2R slot-die coating system. Finally, an optimum range of governing process parameters was proposed using a meta model for improving the mass-production system; the meta model was developed using response surface design as the design of experiment (DOE) methodology.

2. Mathematical study and experimental verification

2.1. Viscocapillary model

The thickness of the coated layer can be estimated and adjusted by a process called premetered coating [19,28]. Eq. (1) gives the mathematical model derived by Ruschak [28] that describes the relationship between the pressure drop across the downstream

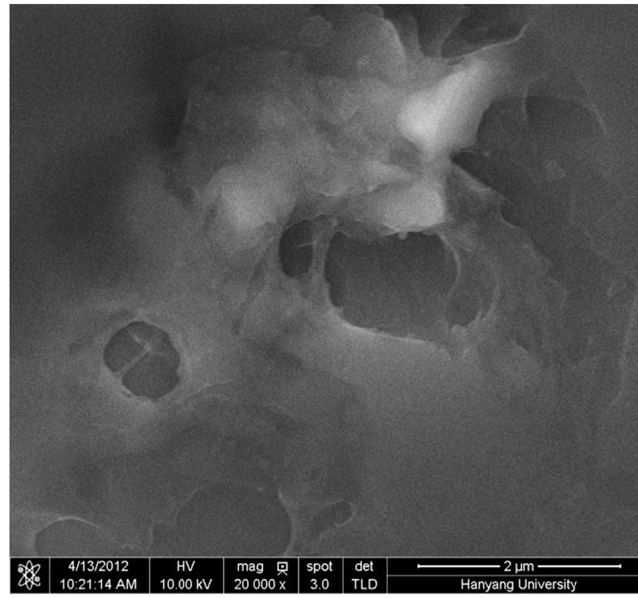

Fig. 1. SEM image of AR-coated surface. The SiO_2 particles are nanosized, so the structure of the AR films during curing varies according to the arrangement of particles. Therefore, process conditions such as the solid content and dry atmosphere are important for improving the transmittance through the formation of a uniform thin film.

meniscus and the film thickness. In this study, the coating window, which represents the minimum wet thickness (t_{min}), was analyzed, based on which it was determined whether the coating bead is stable. The t_{min} value is related to the coating gap H_0 and capillary number Ca, where $Ca = \mu V/\sigma$ (μ: viscosity of liquid, V: coating speed, and σ: surface tension of liquid) [29].

$$t_{min} = \frac{H_0}{1 + 1.49 Ca^{-2/3}} \quad (1)$$

Through the derived mathematical model (1), t_{min} is predicted to be proportional to the coating speed, coating gap, and viscosity of the liquid. As a result, the wet thickness was increased and it converged at a certain point in experiment results [30].

2.2. Simulation and experimental verification

The above-described viscocapillary model was used to simulate AR coating using the R2R process, and the simulation results were compared with the experimental results. In the experiment and simulation, AR solution obtained from HYTC, Ltd., was used. For both the simulation and the experiment, the following parameters were set: coating gap of 100 μm, viscosity of 3.3 cP, liquid surface tension of 18.56 dyn/cm, and solid content of 3 wt%. Furthermore, the viscocapillary model not only represents the tendency toward the minimum wet thickness but is also necessary for analyzing the dry thickness, which affects the performance of the final product. Therefore, in the simulation, the wet thickness after drying was determined by considering the solid content, as given in Eq. (2).

$$th = t_{min} sr \quad (2)$$

Here th is the thickness after drying; t_{min} is the thickness before drying (minimum wet thickness); and sr is the solid content ratio, calculated as $sr = weight\ percentage/100$.

The experiment was conducted using a slot-die R2R machine (SAM, Ltd.). Polyethylene terephthalate (PET) film (SKC Ltd., SH-34, 150 mm width) was used as the substrate. The coating layer thickness was measured by an interferometer (Nanoscan, Ltd., NV-2000).

A comparison between the simulation and experimental data is shown in Fig. 3. Experimental results showed that the coated-layer