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In-situ surface inspection for roll-to-roll process: Towards responsive manufacturing

Hussam Muhamedsalih[1], Mothana Hassan[1], Prashant Kumar[1], Liam Blunt[1], David Bird[2], Dan Kolb[2], Steven Edge[2], Jonathan Howse[3], Andrew Campbell[3]

[1]*EPSRC Future Metrology Hub/ Centre for Precision Technologies (CPT), University of Huddersfield UK*
[2]*Centre for Process Innovation CPI, UK*
[3]*Chemical & Biological Engineering/ University of Sheffield UK*

h.muhamedsalih@hud.ac.uk

Abstract

Roll to roll (R2R) manufacturing is known as a cost-effective process for mass production of flexible products ranging from papers to flexibles electronic devices such as PV cells and displays. Slot-die coating technologies are widely used in R2R as a simple but effective process to deposit inks on moving substrates to form thin film tracks with high uniformity. R2R utilising slot-die approaches is in need of further refinement to produce defect-free ultra uniform thin films with nano-scale thickness coating capability. This presents a challenge as the current status of slot-die printing is that it is an open-loop manufacturing process without sufficient in-process metrology instrumentation. Monitoring sub-micro scale coating thickness and micro-scale defects on metre-scale substrates (e.g. 0.3 m width) moving at high speeds (e.g. 50m/min) poses a significant obstacle. In this work, the authors are aiming to pave the way for R2R to translate toward responsive (closed loop) mode manufacturing by controlling the operation conditions via two optical metrology approaches that can be used as feedback sensors for close-loop responsive manufacturing. The first optical instrument is an in-situ single shot multi-wavelength polarising interferometer to measure the surface topography of coated film "on the fly" during manufacturing (out of plane). The polarisation serves as an instantaneous phase shifting mechanism and the multi-wavelength is employed to generate a long synthetic wavelength to extend the measurement range beyond λ/4 limitation. The surface height information, with nano-scale accuracy, can be used as a feedback signal to the manufacturing process. It will be shown that surface topography measurement can directly be linked to one of the operating variables, namely the slot-die pump flow-rate. The second optical instrument is a machine vision senor for edge and defect detection (in plane) using Otsu thresholding algorithms. It is demonstrated in this paper that the edge uniformity along the printed track can be quantified as metric values. The complete system demonstration shows also that track defects, track geometry and track topography (in and out of plane measurement) can be detected and successfully classified in real time. Fluoropolymer, silver, and Carbomer Ethanol Methylene Blue (PAA-C2H6O-MB), printed ink samples on Ti coated polymer substrates and a PTE substrate, have been utilised in this study as an exemplar combination.

Thin film inspection, roll-to-roll printed coating inspection, edge and defect detection, machine vision

1. Introduction

Roll-to-roll coating/printing (R2R) is a viable process for the production of large area flexible devices. R2R has the potential to save production cost if the print operating variables and web (substrate) handing are well controlled and optimised. R2R manufacture has developed capabilities from conventional paper, foil and textile process to high value components such as optoelectronics or graphene-based devices. Such devices have high demands on the precision of the processing to tight manufacturing specification [1]. For example, thin film thickness for flexible electronics applications, such as capacitors films, needs to be controlled to sub-micron level across meter-scale web widths. Slot-die coating technologies are commonly used in R2R to deposit conducting thin film inks to a wide-range flexible substrates. In slot-die coating, the uniformity of thin films is directly linked to the operating variables such as ink pump flow-rate, speed of the web, ink drying, and the gap between the slot-die head and the web [2]. Film defects are mainly related to the web handling [3]. As such, imperfections in R2R operation lead to unwanted thickness/width variation or defects in thin films, resulting in low productivity and large amount of waste. Unfortunately current practice is that R2R processes are forward-loop systems with no feedback to adjust the coating operation. The transition to a close-loop approach is a way forward to upgrade R2R to responsive mode manufacturing and thereby enhancing process productivity.

Real time film surface monitoring providing reliable quantitative information to process controllers is the key to facilitating successful R2R closed loop processes. The present authors have demonstrated static optical surface metrology for thin film inspection [4]. This paper discusses the combination of two real-time (dynamic) surface inspection methods that potentially can be used as feedback sensors. The sensors provide both in plane and out of plane data regarding the R2R coating processes. The first method is a single shot multi-wavelength scanning interferometer (MPI) (out of plane) and the second is a machine vision sensor (MVS) for coat edge monitoring and defect detection.

2. Multi-wavelength Polarising Interferometer MPI (out of plane)

The MPI configuration, shown in Figure 1, consists of a Michelson polarising interferometer and four detection optical arms. Each detection arm has a colour CMOS camera placed after a polarisation arrangement to generate a single RGB interferogram shifted by π/2 sequentially. Four colour interferograms are captured at single exposure time (< 1 ms) to negate the surface vibration. The frames are transferred to the computing console for analysis. The system operation principle has been reported in our previous publication [5]. The MPI has been installed onto a R2R production line at the Centre for Process Innovation/UK, see Figure 1.

In the present work, a slot-die printer was used to print Fluoropolymer ink into Ti coated polymer substrate at 1m/min web speed. The MPI was aligned with the edge of the track to measure the ink top surface real time with respect to the substrate, as shown in Figure 2.a. The pump flow rate was then changed from 1500-4000 µl/min incrementally. Based on MPI measurement, shown in Figure 2b, it can been seen that the variation in coating thickness can be measured dynamically during the pump flow-rate change process.

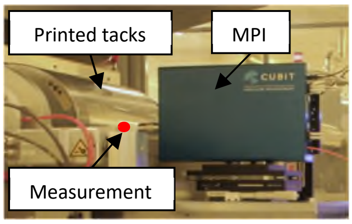

Figure 1. MPI installed onto R2R manufacturing

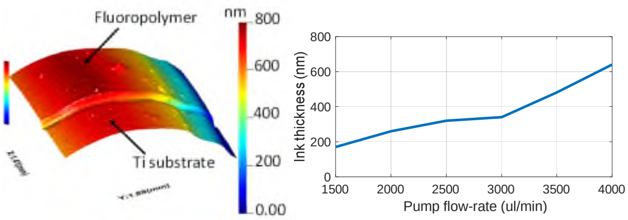

Figure 2. (a) Web real surface measurement (b) film thickness vs pump flow-rate *(Note; curvature dure to roll form)*

3. Machine vision sensor MVS (in of plane)

The MVS, described in [6], was used for in-plane inspection to identify defects and print track edge irregularities on the web that can produced during the slot-die coating process. The edge irregularities/straightness was analysed using the Otsu thresholding algorithm. The foreground and background pixels represented by the ink track and the web substrate were successfully distinguished after tuning the threshold value. As such, the produced segmented results can be used to easily extract the track edge profile. The authors have reported previously that the lateral arithmetic average edge deviation calculation, named as (Ra_{LAT}), can be quantified to indicate the edge quality as shown in Figure 3. In this case Silver Ink on Polyethylene Terephthalate (PET) substrate was used to verify Otsu performance.

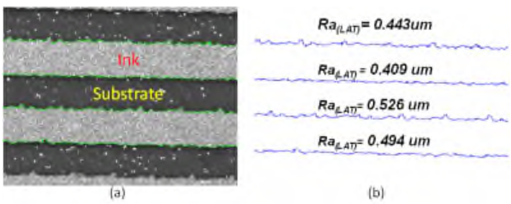

Figure 3. (a) MVS captured image (b) Extracted edge profiles

This MVS work also focused on extracting the presence of defects for classification in order to be linked later to R2R operation conditions. To extract defects, a template image was captured from a defect-free area on the sample. This reference template can be convolved to images captured from the substrate during R2R operation to subtract original features and extract unexpected features (i.e. defects). The defects then can be further processed by a simulated defects template for classification purposes as described in [7]. This defects analysis concept has been verified by using the MVS to dynamically inspect moving web of PAA-C2H6O- MB/PET. Figure 4 shows defects detection and classification results collected dynamically. The lighter spots in Figure 4a are defects in the ink. It can be seen that this sensor can successfully extract and classify such defects as shown by the yellow frame in figure 4b.

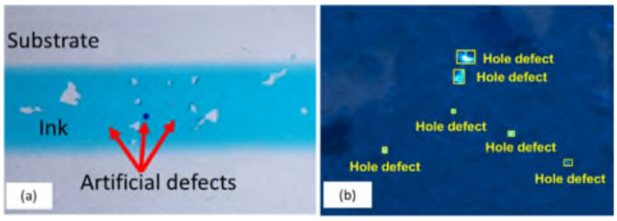

Figure 4. Defects detection; (a) PAA-C2H6O- MB sample (b) MVS results

4. Conclusion

To translate R2R process from forward-loop to close-loop, responsive mode, manufacturing is a core requirement. Consequently the existence of feedback sensors to provide quantitative information is necessary. The two combined optical sensors outlined in this work provide the basis for scale up to a full manufacturing environment where their output is directly linked to the operation conditions. For example, it has been found that surface thickness extracted from the surface topography information measured by MPI can be directly linked to the pump flow rate. As such, any undesirable thickness variation can be measured with nano-scale resolution and fed to manufacturing controller for optimisation. The MVS has also demonstrated an effective methods for defect/edge defection and classification. The metric information for the edge straightness can linked to the web handling such as the web tension or slot die clogging. Research continues to investigate methods for optimising the operation variables and web handling by using manufacturing controllers connected to optical sensors.

Acknowledgement

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