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Original Citation

Muhamedsalih, Hussam, Blunt, Liam, Martin, Haydn, Hamersma, Ivo, Elrawemi, Mohamed and Feng, Gao (2015) An integrated opto-mechanical measurement system for in-process defect measurement on a roll-to-roll process. In: Laser Metrology and Machine Performance XI, LAMDAMAP 2015. EUSPEN, Huddersfield, UK, pp. 99-107. ISBN 978-0-9566790-5-5

An integrated opto-mechanical measurement system for in-process defect measurement on a roll-to-roll process

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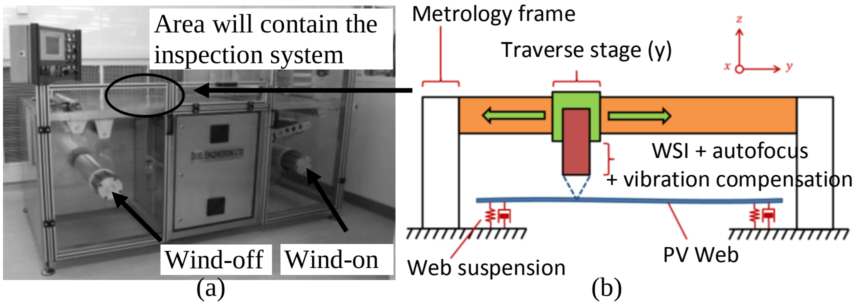
Abstract

This paper reports on the recent work carried out to develop and implement a high precision on-line optical measurement system with the aim of providing defect detection and characterisation for ALD coated vapour barrier films produced by a roll-to-roll process. This proof-of-concept system is designed to detect and measure pre-existing defects on the film and define their size, location, form and density. The aim is to be able to detect defects in a thin film Al_2O_3 layer that are critical to vapour barrier performance, and eventually provide valuable process control information. Such an inspection system must be fast in order to evaluate large areas involved (500 mm width foil) at high magnifications. In addition the flexibility of the foil introduces challenges in terms of dealing with surface deviation away from an ideal plane and vibrations. Our solution is a wavelength scanning interferometer (WSI) combined with two kinematic stages, vertical (for auto-focus) and a traverse stage to provide full coverage of the foil. A porous air-bearing conveyor system is used to hold the foil at a fixed height and improve the flatness of the film relative to the measurement plane. This paper describes the principle and design of the inspection system.

1 Introduction

The atomic layer deposition technique (ALD) is used to apply a thin (40-100 nm thick) barrier coating of Al_2O_3 on polymer substrates for flexible PV cells, to minimise and control the degradation caused by water vapour ingress. However, defects appearing on the film surfaces during the Al_2O_3 ALD growth have been seen to be highly significant in deterioration of the PV module efficiency and lifespan [1]. Therefore, an on-line inspection system needs to be implemented to optimise the roll-to-roll manufacturing process for coated polymer film. Two main conditions need to be fulfilled by the inspection tools; i) the measurement must be fast and non-contact ii) the measurement must be carried out in a “noisy” working environment. The optical interferometry techniques can be potentially used as a solution for such application but they are extremely sensitive to environmental noise such as mechanical vibration, air turbulence and temperature drift. George [2] reported that a single shot interferometry system “FlexCam” developed by 4D Technology being used currently to detect defects for PV barrier films manufactured by R2R technology. This fast measurement system can acquire 3D surface and avoid environmental disturbances, but this technology has a limited vertical range (sub-micron - few micrometre), which is less than the combined barrier film thickness (125 µm) of the barrier film. To extend the measurement range, the wavelength scanning interferometer (WSI) can be employed for deep defect measurement. This paper reports on the installation of WSI combined with kinematic stages to enable on-line and full coverage inspection for the flexible foil on a standalone film rewinder. The practical setup, operation principle and preliminary results are all described in the paper as well.

The roll-to-roll stand has been implemented at the Centre for Process Innovation (CPI) Ltd as proof of concept demonstrator to investigate the Al_2O_3 ALD coating process by measuring and classifying all relevant defects on polymer film, see Figure 1.a. The WSI is used to provide surface topography with field of view of 0.5 x 0.7 mm per single measurement using 5X objective lens. For full coverage inspection, the WSI needs to be mounted onto a traverse stage, as shown in Figure 1.b, to be stepped incrementally by the horizontal dimension of field of view (FOV) over the full width of the web (i.e. 0.5 mm/500 mm). At the end of each width the web can be moved incrementally by the vertical dimension of FOV (i.e. 0.7 mm).



(a) (b)

Figure 1: (a) The rewinder/unwinder stand (b) Diagram of opto-mechanical inspection system

The alignment of the foil surface relative to the WSI focal plane is critical in this application. It needs to consider several parameters, namely the focal depth and acceptance angle of the objective lens, the flatness of the foil, the roll/pitch errors of the traverse stage and the environmental disturbances. To maintain a sufficient alignment, a vertical stage is used for auto-focus WSI on the top surface of the foil with accuracy and repeatability better than the focal depth of the objective lens. Also, a porous air bearing conveyer is used to improve the flatness of the foil at fixed height. A built-in vibration compensation system in the WSI can actively stabilise the interferometer during the measuring process.

2 WSI principle

WSI, as shown in Figure 2, is employed to measure the surface topography of the barrier coating and is capable of generating surface maps with unambiguous height, without the well-known 2π phase ambiguity limitation. The interferograms are produced with no mechanical movement but by scanning the wavelength of a halogen light in the visible region (683.4 nm-590.9 nm) using an acousto-optic tuneable filter (AOTF). Such a measurement methodology can provide significant enhancements in speed compared to comparable methods such as white light scanning interferometry (WLSI). In addition, the WSI can be stabilised against environmental disturbances by using an active control of the reference arm, thus enabling nanometre scale measurements with large amounts of environmental isolation [3]. This active control consists of a reference interferometer, which provides positional feedback, and a piezo-electric transducer (PZT), which moves the reference mirror. The PZT is driven by a PI controller to track the altering in the optical path due to environmental disturbance such as mechanical vibration and refractive index drift.

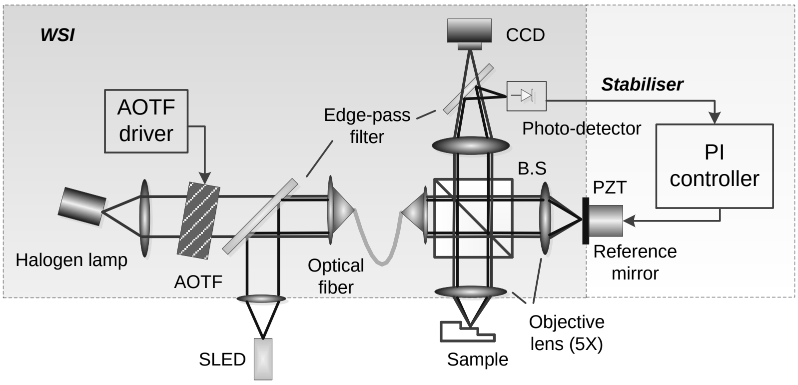


Figure 2: Configuration of the WSI

The reference interferometer is multiplexed with the WSI to share the same measurement optical path using an edge-pass filter (dichroic mirror) and a super luminescent diode (SLED) light source having a central wavelength of 820 nm. The intensity of the generated fringes is detected by a photo-detector which monitors the SLED light only, using a dichroic filter that reflects the IR light to the detector and allows the scanned visible light to pass through to the CCD. This control loop system can compensate for disturbances in the optical path length up to a few microns at 102 Hz and stablise the WSI for wavelength scanning process.

During the measurement process, 256 interferograms are captured over a full field of view using 5X magnification objective lens and 640x480 CCD pixels. A periodic spectral interference pattern produced for each captured pixel is analysed individually using Fourier transform algorithm. This analysis is widely used to extract the phase from periodic fringe patterns by filtering out the DC interference term and the phase conjugate from the power spectral density obtained via the discrete Fourier transform. The extracted phase distribution suffers 2π ambiguity that can be removed using one-dimensional unwrapping method.

The evaluating process for areal topography requires long processing time when CPUs traditional sequential execution programs are used. The full analysis of all the pixels is, therefore, accelerated by parallelising the computation with a many-core graphic processing unit (GPU). The WSI can capture and generate a full areal topography in 3.7 seconds. The CUDA C program is used to achieve the data parallelism using a GPU device, hence increasing the measurement throughput, demonstrated. Typically, in a sequential programming model, the program generates a main thread that executes functions in a sequential manner. In contrast, the CUDA parallel programming model generates thousands to millions number of thread (typically equal to the captured frames size) to execute data-parallel functions, known as kernels, in a parallel manner. In this application, 307200 threads are generated to analyse each pixel individually in a parallel manner. The computing time is accelerated to approximately 1.1 second compared to 31.9 second using conventional sequential programming approach [4].

3 Air-bearing system

The precision inspection for roll-to-roll process demands an accurate non-contact web handling solution that supports the film at fixed height and maximize the flatness of the web relative to the measurement plane. The handling solution should also be approved for use in clean room environment. It is the air bearing conveyor that can satisfy such conditions if uniform dry air pressure is supplied across the entire air bearing area with a vacuum pre-tension force to hold the foil. In this application, a conveyor type H-Series from New Way Ltd was used to supply uniform clean dry air (CDA) pressure, through a porous medium with a thin air gap, resulting in a more consistent fly height and better flatness across the full width of the flexible foil web. This technology can also act as a stop-gap filter, trapping any particles which may have escaped the filter system.

The conveyor performance was investigated by IBS Precision Engineering [5] using an optical sensor which scanned across the foil web after supplying 2 bar air pressure and vacuum pressure ranges 0-0.3 bar with 0.05 incremental step, see Figure 3. It has been found that the conveyor can hold the web with local height variation of <5 μm under 0.05 bar vacuum. The worst case peak to peak variation is found to be < 25 μm over the 60 mm foil width without vacuum pressure. This height variation is within the focal depth limit of the objective lens used in WSI (e.g. the focal depth for 5X objective is equal to ±14 μm).

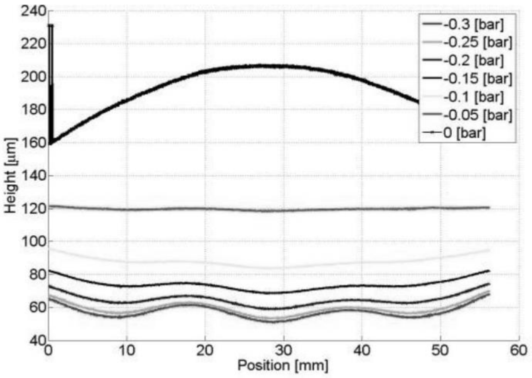


Figure 3: Air bearing performance at 2 bar air pressure when altering the vacuum pressure [5]

4 Auto-focus function

An effective auto-focusing methodology is crucial to the successful implementation of the WSI for large flexible substrate measurement. Although the flexible substrate is held by a porous air-bearing conveyor, the surface undulation is still substantial across the 500 mm web width. Fast, automated positioning of the WSI head so its focal point is at the top layer of Al_2O_3 barrier is needed which must also be robust against the possibility of mis-focusing due to the multilayer structure of the web.

The auto-focus method is based on tracking the peak of the coherence envelope of the reference interferometer sourced by the SLED when the head is moved normal to the web to scan the focal plane of the WSI objective lens using a stepper motor. Simultaneously the intensity response is monitored by the reference interferometer, with the maximum intensity (coherence envelope peak) being found to be the point of focus. Throughout the translation, the position of the film is acquired continuously from the encoder of the stepper motor in order to map the physical position of the translation stage to peak position of the coherence envelope. This information allows the stage to move to the precise point of focus after the scan. The speed of the auto-focusing method is dependent on the speed of motorised translation stage. For the current setup, the auto-focus routine, using a 1 mm translation distance, took approximately 0.6 second.

The limiting factor for the auto focus method is the number of tilt fringes which results in the degradation of signal-to-noise ratio of the feedback signal. Experimentally, it has been determined that a sufficient interference signal can be obtained for effective autofocusing operation when there is more than 5 fringes (equivalent to 2.4 mrad surface gradient) appear across the WSI field of view, see Figure 4. Increasing the number of fringes across the active photo-detector area, which is equal to 0.5 mm^2, will average out the coherence intensity and hence degrade the feedback signal.

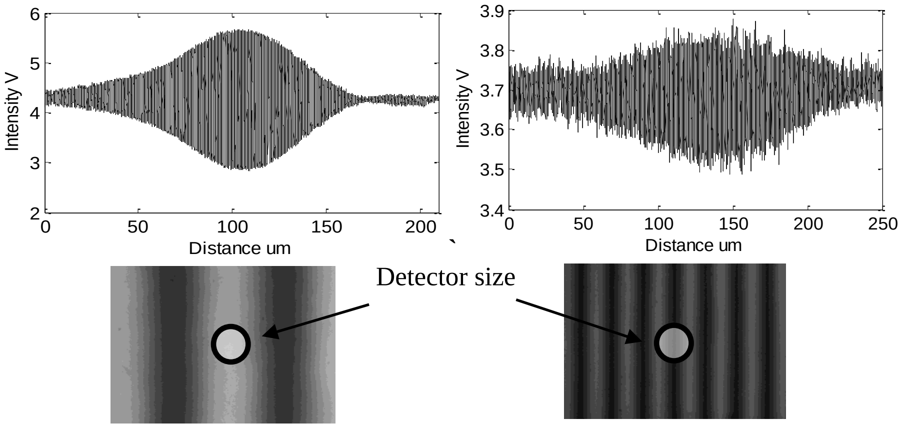


Figure 4: The coherence intensity response with its corresponding FOV.

The repeatability of the auto-focus system has been tested on the surface of a standard artefact sample supplied by the National Physics Laboratory (NPL). The alignment of the system produced 3 fringes across WSI field of view. It has been found that the system repeatability within one standard deviation (σ) is 5.3 μm, see Figure 5. This value is less than the focal depth of 5X objective lens used in this test. It is also found that maximum difference between the auto-focus positions is equal to 24 μm which is still less than the focal depth of 5X objective lens (i.e. less than 28 μm).

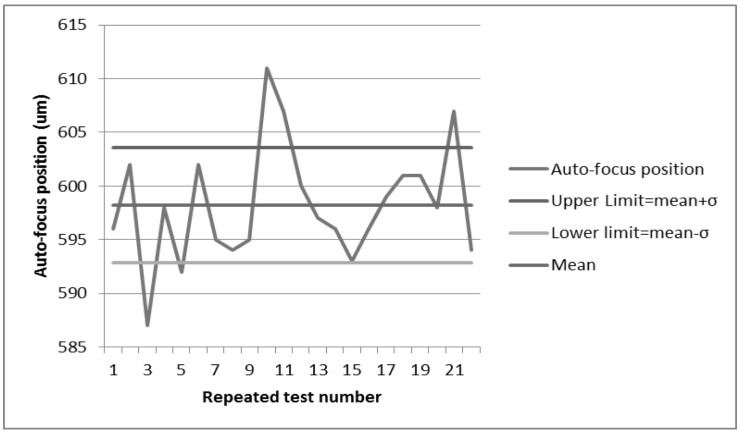


Figure 5: The repeatability of the auto-focus system

5 System Implementation and operation

The opto-mechanical inspection system has been mounted into a metrology frame using kinematic adjuster as described in Figure 6.a, resulting minimum tilt fringes across WSI field of view (i.e. less than 5 fringes per FOV). The porous air-bearing conveyor is placed underneath the polymer film to stabilise the web at fixed height. A standard artefact supplied by NPL has been mounted beside the edge of the foil web and aligned with respect to the conveyor in order to justify the WSI performance. The final setup of the system is shown in Figure 6.b.

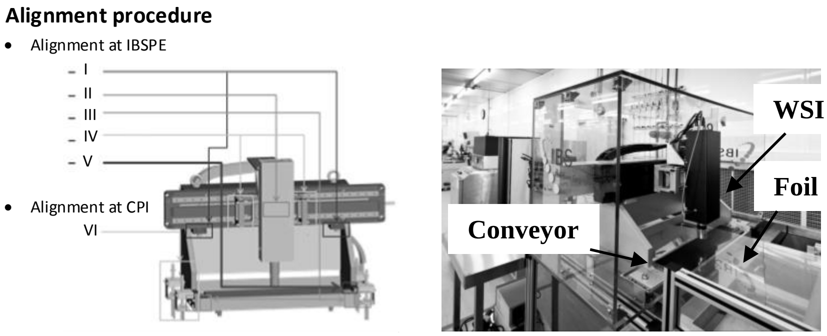


Figure 6: (a) Opto-mechanical inspection system, where **I** is align Y-stage w.r.t. conveyor in Z and R_x, **II** is align WSI w.r.t. Y-stage in Z, **III** align conveyor w.r.t. WSI in Ry, **IV** align WSI w.r.t. conveyor in Rx, **V** align artefact w.r.t. WSI in Z, R_x and R_y, **VI** align setup w.r.t. foil (b) Integration the inspection system onto rewinder stand.

The start position is located at the artefact such that the operation of the system is initiated by measuring the 1.2 µm step height sample, see Figure 7. It has been found that the measurement precision is better than 20 nm. The WSI is translated incrementally over the web width while the foil is stationary. Instead of inspecting a foil coated by Al_2O_3 barrier, gold coated PET film has been measured to obtain preliminary such that three defects were detected as shown in Figure 8. The measurement throughput to cover 500 mm width is approximately 2 hours using 5X objective lens. The overall data size for full width (i.e. 500 mm x 0.7 mm) is larger than 300 megabyte.

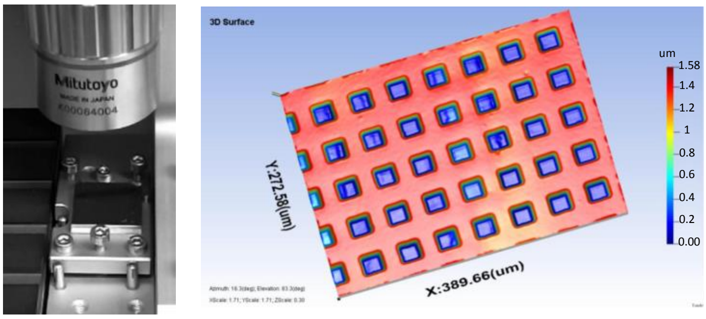


Figure 7: Artefact measurement for calibration purposes

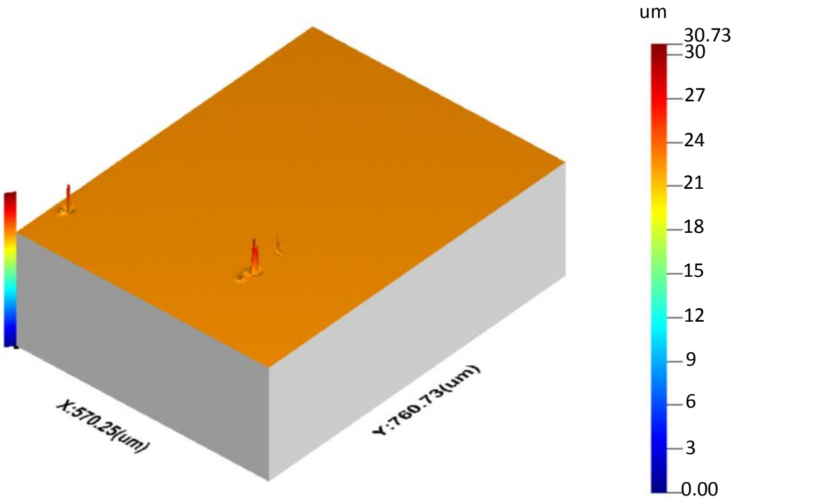


Figure 8: PET film areal measurement using WSI

6 Conclusion

It is well established that the efficiency of flexible PV is correlated to the WVTR which is dominated by the presence of large defects in the barrier layers. Implementation on-line defect detection systems can enhance the he roll-to-roll (R2R) manufacturing process. The WSI can be considered as a solution for R2R process as combined to traverse and autofocus stages and air bearing conveyor. This opto-mechanical system can measure wide foil area in spite of environmental disturbances and without interaction by the operator for alignment or focusing the instrument.

7 Acknowledgement

The authors would like to thank the EU for providing funds to carry out this work via the NanoMend project NMP4 LA-2011-280581 and the EPSRC for funding the UK Centre for Advanced Metrology.

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