DANCES WITH FOILS

In-line interferometry of nanometer-scale profiles in flexible electronics has been developed for application on a moving flexible foil. The solution developed by IBS Precision Engineering includes control techniques for tracking in both the travel and the orthogonal direction, and stabilisation techniques for the vertical direction. Foil handling has been optimised to reduce damage to sensitive foils. The interferometric system has been demonstrated on a pilot line, handling photovoltaic foils with ultra-low reflectivity, measuring nanometer features – this is a world first.

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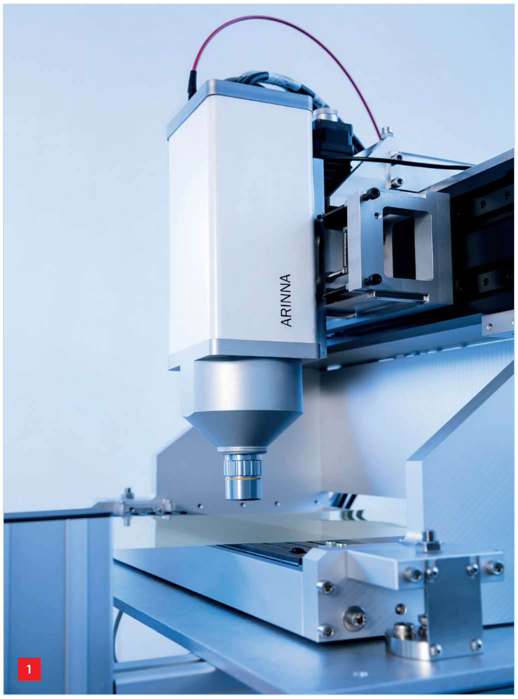
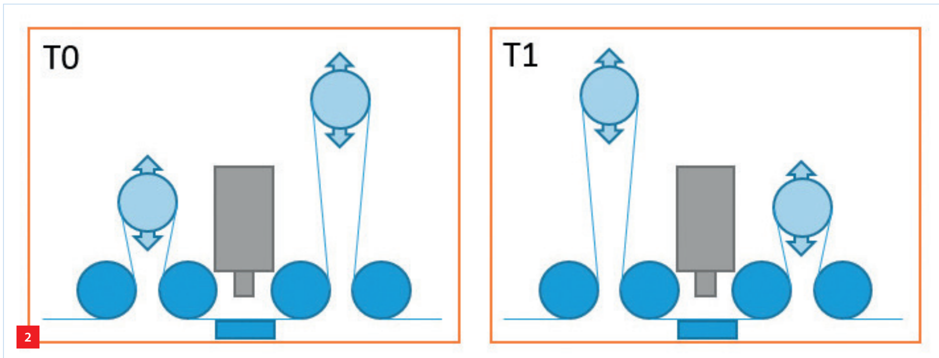
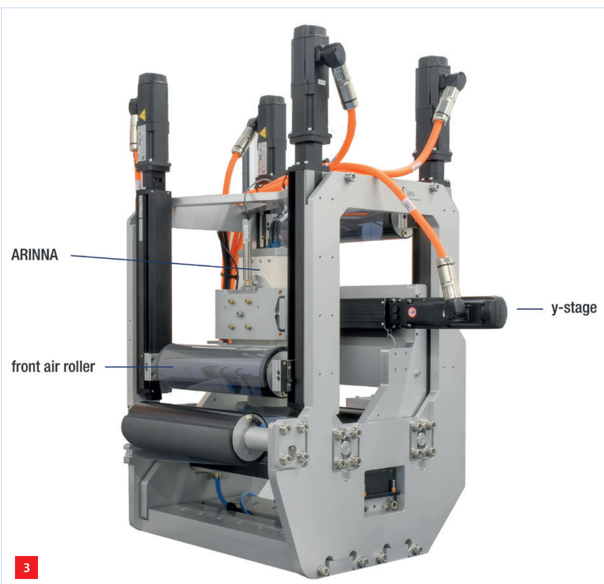


1
The ARINNA interferometer located above a moving foil.



2
Schematic of the dancer. Dark blue: standard rollers. Light blue: cylindrical porous media air bearings (airturns).



3
Dancer as built.

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In the production of flexible electronics, such as organic LEDs or photovoltaic foils, often nanometer-scale features critical to the device performance are implemented. In-line 3D metrology of such profiles promises to revolutionise the production process by avoiding time-consuming off-line measurements for process control. Achieving such measurements in a roll-to-roll environment is a precision challenge.

Wavelength-scanning interferometry

An areal interferometer, named ARINNA, has been developed for quality control of surface features at the nano- and microscale in production. The measurement technique employed by ARINNA (Figure 1) is based on the principle of wavelength-scanning interferometry (WSI). The technique involves the capture of a set of interferograms across a range of wavelengths incident on the sample or product.

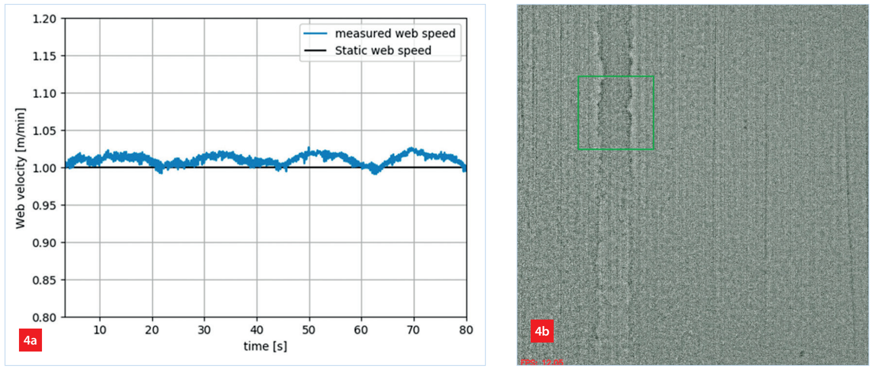
The interferometer is able to measure discrete step heights and surface quality with a vertical resolution < 2 nm, as verified by earlier experiments [1]. In-line measurement of printed electronic foils requires the ability to measure low-reflective samples, 'capture' of the moving foil, stabilisation techniques and methodologies to overcome residual surface vibrations. Measurements can be taken across the full width of the web using *y*-motion control and autofocus functionality in the *z*-direction. Feedback from the

ARINNA head is used to identify the optimum z-position for measurement. This allows for minor tilts in the foil along the y-direction.

An in-line system was developed to measure laser scribes in organic printed voltaics (OPVs), as elaborated below. Scribe depths and widths were of the order of 100 nm and tens of microns, respectively.

Dancer development

Nanometer features on foils moving at 1-5 m/min were targeted. Several potential strategies for capturing images from a moving web were explored, including mechanical



(a) Encoder-measured web speed.
(b) Marker detection (green square); its position is used to verify dancer speed accuracy.

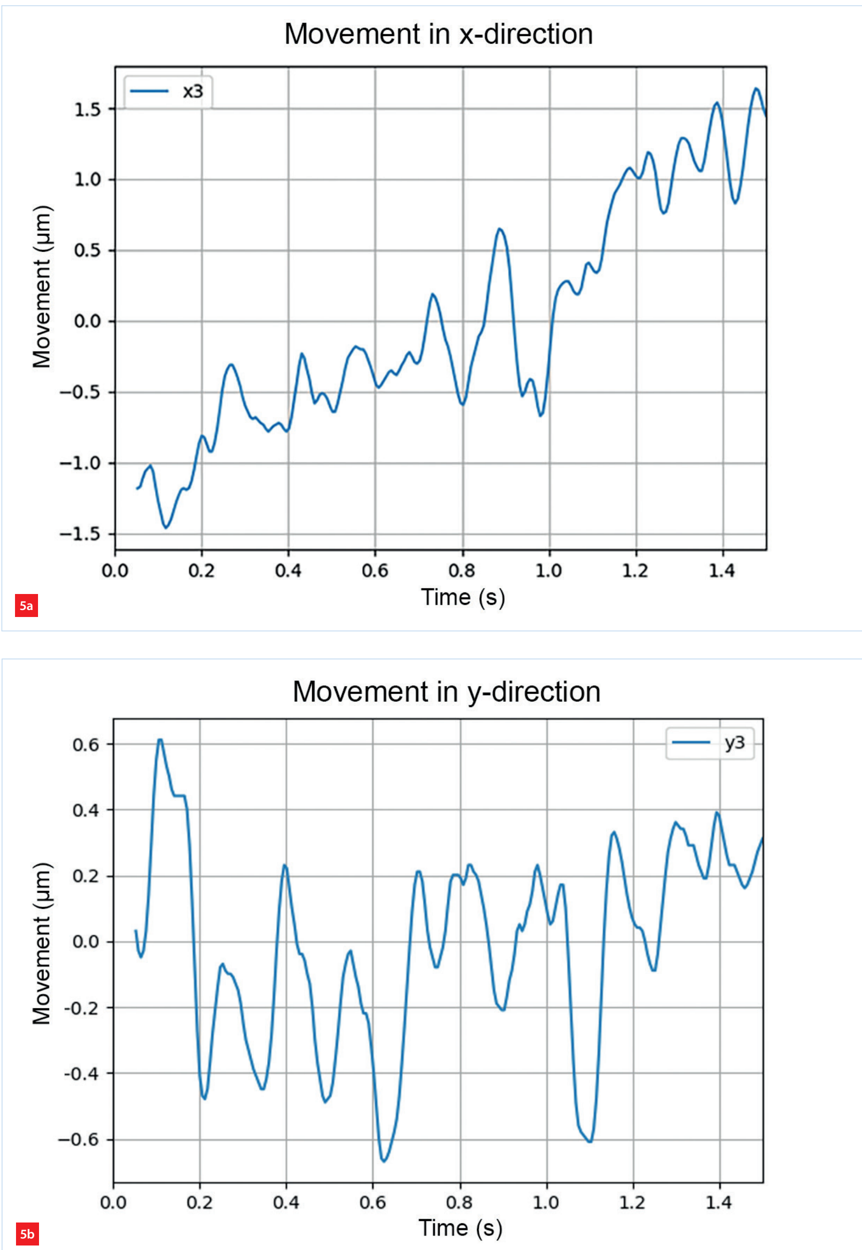
(chasing the foil) or electronic (tracking in the camera). Given limited integration space in the final manufacturing line a so-called dancer solution was chosen; here, dancing refers to two airturns moving up and down in (anti-)sync, to keep the foil at a stable position under the interferometer. A schematic is shown in Figure 2.

At T0, the left airturn (cylindrical porous media air bearing) starts in the lower position while the right airturn starts in the higher position. A buffer action is started to enable the remainder of the roll-to-roll line to continue production uninterrupted while the measurement occurs. Then, the left airturn moves with half the speed of the web in the vertical direction towards position two. The right airturn follows the left airturn with the same speed in the opposite direction.

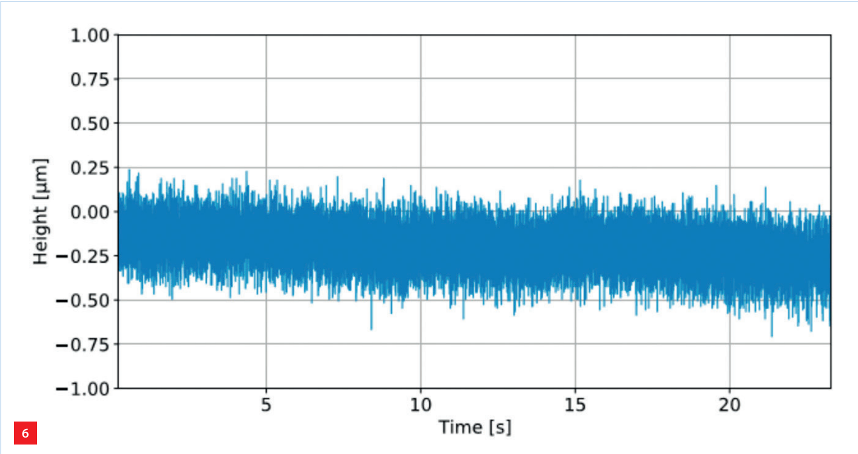
At T1, the right airturn lies in the lowest position and the reverse process begins. Four contact rollers and two airturns are used so that front contact is not made with the sensitive web. Buffering is triggered by a marker on the foil or, alternatively, can be controlled by a set of user-chosen intervals. Figure 3 shows the dancer as built.

During laser-scribe measurements, the web under the measurement system should be stationary in x, y and z, while the rest of the line continues at a typical speed between 1 and 5 m/min. Most critical is the movement perpendicular to the travel direction, which should be smaller than the width of the laser scribe, hence of the order of microns.

To evaluate the dancer performance, new object tracking software was implemented. This software can track an arbitrary object for the duration of the interferometer image capture, by analysing the movement of the object during the wavelength sweep used to measure the surface. So, not only the marker on the edge of the web can be analysed but any position on the web. This software is used to detect the x/y-accuracy the dancer achieves.



Measured web displacement with the improved speed monitoring.
(a) x-Position of a laser scribe on the web during dancing (0.8 µm standard deviation).
(b) y-Position (0.3 µm standard deviation).

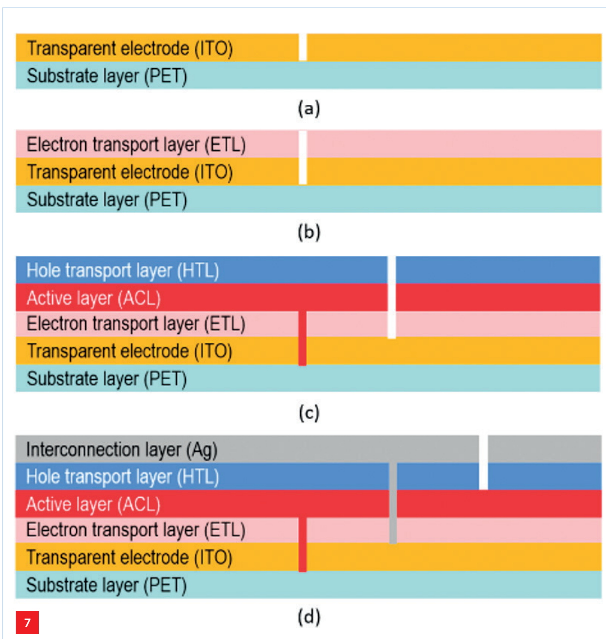


z-Stability of the web during dancing and stabilisation with air table.

Figure 4a shows the encoder-measured web speed at the entrance to the dancer in the IBS line, whereas Figure 4b shows object detection on a laser scribe. The marker is used to measure the movement in *x* and *y* during dancing – the target is zero motion in *x* and *y*. Figure 5 presents the measured displacement of the web with the improved speed monitoring. The data of Figure 5a shows the *x*-direction performance that was measured as stationary, with an 0.8 µm standard deviation. From the data in Figure 5b, a standard deviation of 0.3 µm has been obtained in the *y*-direction.

Web stabilisation

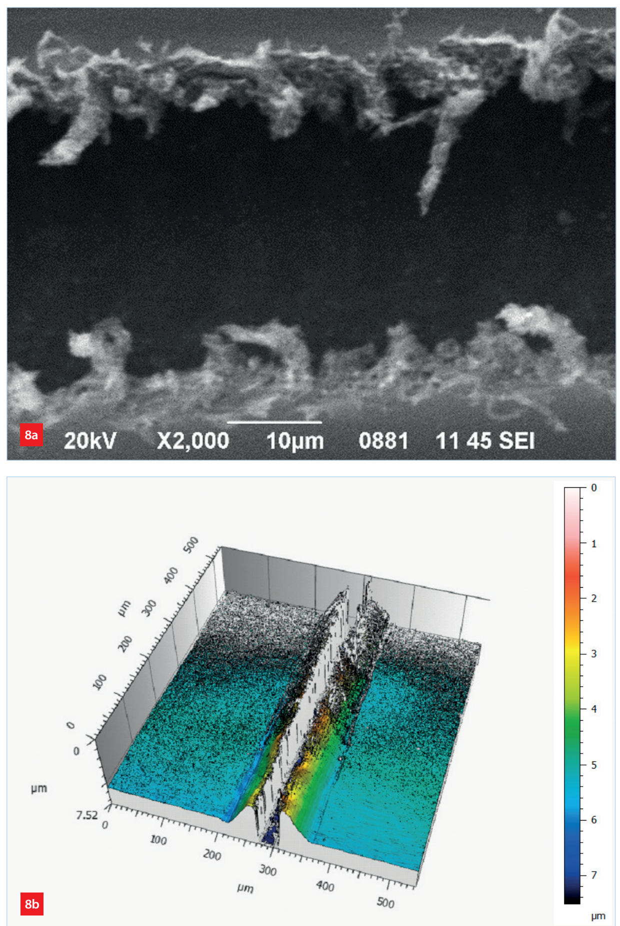
Laser-scribe depths can be measured by the interferometer to an accuracy of nanometers. It is critical that the web is stable in the vertical z-direction during measurement to achieve these accuracies. Typical motion of webs in the *z*-direction during production is of the order of more than 300 µm (as previously measured by IBS). To stabilise the web below the ARINNA in the vertical direction, an air table has been placed under the web. The air table utilises both vacuum and air pressure to set pretension on the web and cancel any vibrations from the roll-to-roll line. To cancel any vibration induced by the dancer motors, the metrology frame has been decoupled from the dancer frame. Figure 6 shows the *z*-stability during dancing to be of the order of +/– 0.25 µm.



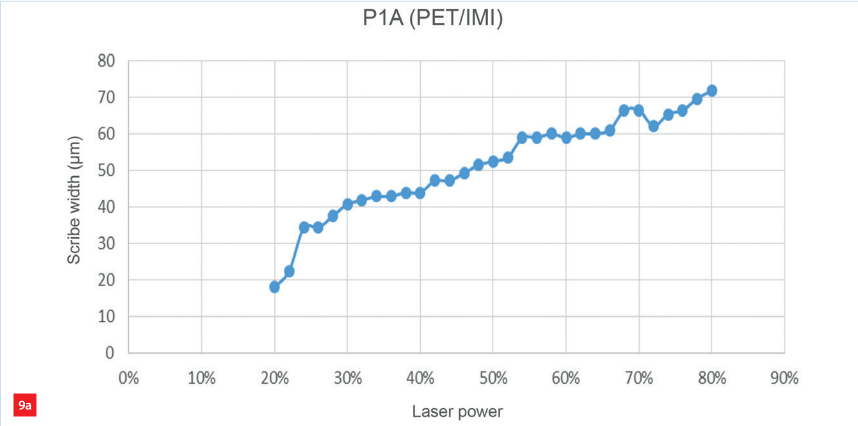
Schematic representation of the organic electronics stack that was investigated, with the various types of laser scribes.
(a) P1A.
(b) P1B.
(c) P2.
(d) P3.

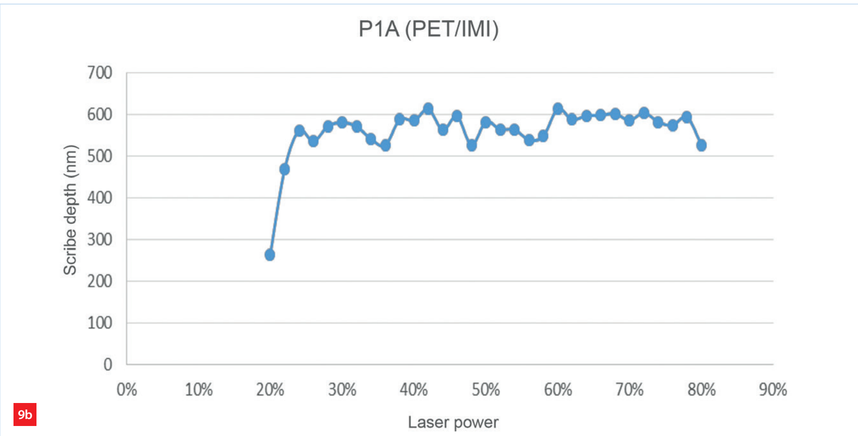
Vibration compensation

With the foil stabilised in *x*, *y* and *z*, the surface topology can be measured. Within the interferometer, compensation is applied for residual vertical motion of the foil during data capture. Advanced modelling identified a number of improvement opportunities, including enhanced hardware filtering and optimised microprocessor speeds, to increase the bandwidth of this vibration compensation. Applying these improvements enhanced the bandwidth of the vibration compensation from 280 Hz to 650 Hz. This in turn has enabled stable measurement of webs floating on the air table.



Comparison between SEM image (top) and ARINNA interferometer measurement (bottom) for the P3 scribe; all units µm.





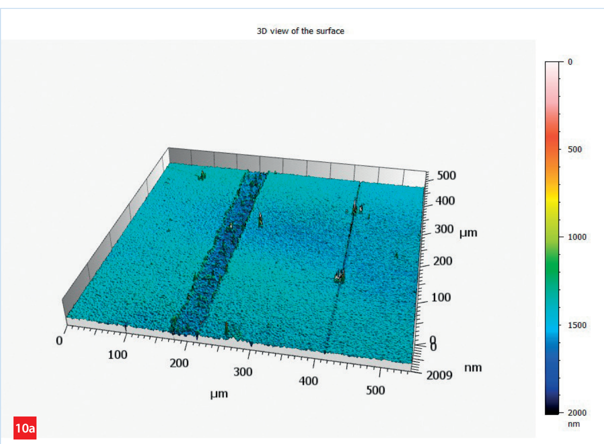
P1A scribe measurements as a function of laser power.
(a) Width.
(b) Depth.

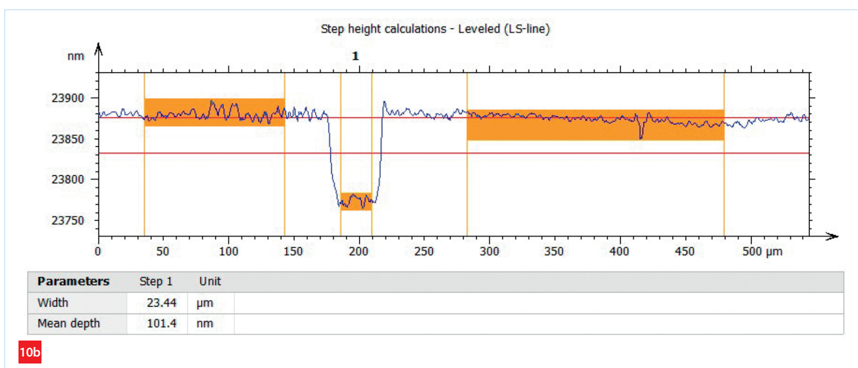
In-line measurement

The OPV samples that were measured are shown in Figure 7. Laser scribes are made at four stages in the processing of these devices. Scribe depths vary from 100 nm for the P1A type to 1.5 µm for P3. Scribe widths are of the order of tens of microns. OPV samples have by definition low reflectivity. Thus, ARINNA was optimised to enable measurement at low return-light levels. This included both hardware updates to increase the incident light and software updates to accommodate potentially higher noise levels. To our knowledge the measurements presented here are the first-ever topological surface measurements for such materials. When manufacturing such devices, SEM (scanning electron microscopy) measurements have typically been used to assess laser scribes. A small piece of the print run is removed and sent for analysis, which typically takes more than a week. Measurements provide 2D data only, indicating a scribe width. Quantitative interpretation of the images by a person is used to confirm the form of the scribe (wall edges, debris, etc.)

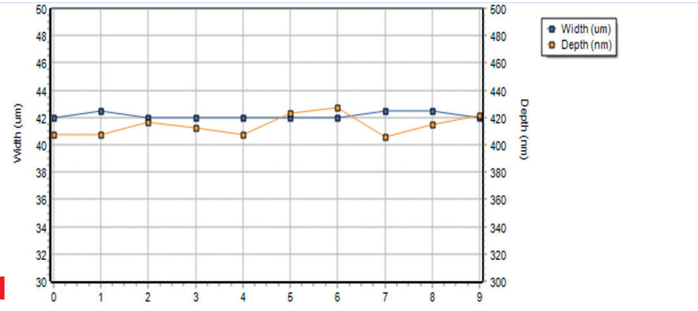
First measurements from the interferometer were compared to SEM images. An example is shown in Figure 8, where features apparent at the base of the scribe are also present in the surface topology measurement by the interferometer. Figure 9 shows measurements for P1A scribes in PET/IMI (PET is a standard plastic substrate used in printed electronics; IMI stands for insulator/metal/insulator). Here, the laser power has been varied from 20% to 80% of maximum power. The scribe width is seen to increase continuously from 20 µm to 70 µm. At the same time, the scribe depth is seen to increase between laser power levels of 20% to 24% and thereafter plateau at the nominal depth of 100 nm, as the scribe has cut through to the PET. In-line measurements of a P1A scribe in PET/ITO (indium tin oxide, one of the most widely used transparent conducting oxides) are shown in Figure 10, on foil moving at 1 m/min. The cross-section shows a scribe depth of 100 nm, in line with the expected ITO layer thickness.

The system has been developed to provide automated measurement at a predefined time interval. Automatic feature extraction is performed for surface features, in this instance the scribe width and depth. A validity check is made against pre-set tolerance values. TCP/IP communication is used to send the depth and width values to a client to allow for laser power adjustment. A typical trend graph is shown in Figure 11.





P1A scribe measurements in PET/ITO on foil moving at 1 m/min, showing the depth profile.
(a) Bird's eye view.
(b) Cross-section.



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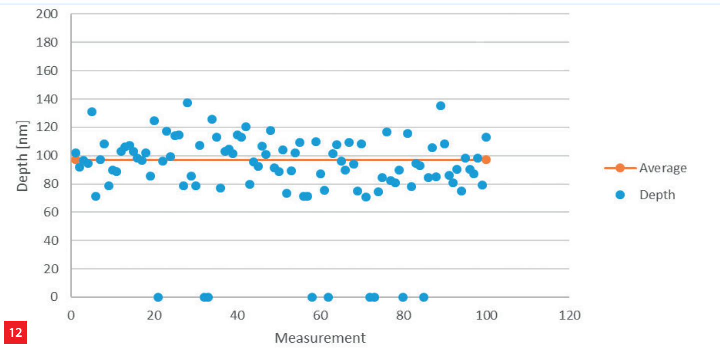
Trend graph of laser scribe depth and width measurements taken in-line at 20-s intervals.



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100 Scribe measurements measured in-line at 1 m/min.

Statistical analysis of 100s of data measurements in a fully stationary setting (the foil not moving) was used to identify the impact of factors including light intensity, exposure time and interferometer optical settings. From these, optimum conditions were identified. A dataset with the preferred settings comprised 367 measurements. The mean depth obtained from this set for a laser scribe of nominal depth 100 nm was 104.7 ± 1.0 nm. The standard deviation of the measurements was 9.5 nm, the standard error of the mean was 0.497 nm. A further 100 measurements were taken of the same foil moving at 1 m/min, as shown in Figure 12. The tolerance range was set between 50 and 150 nm. Nine out of the 100 measurements were seen to fall out of the tolerance range. The mean depth obtained from the remaining data set was 96.96 nm. The standard deviation of the measurements was 15.3 nm, the standard error of the mean was 1.92 nm.

Conclusion

For the first time, laser scribes have been measured interferometrically for OPV samples. Measurements have been successfully made in-line across the full web width using a dancer combined with autofocus capability and feature extraction.

REFERENCE

[1] IBS, "Robuste Oberflächenmessung mit Interferometrie", *Mikroproduktion*, 04/15, pp. 64-68, 2015.