Laser based metrology for First Solar Series 6 module manufacturing packaging process control

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Metrology development was a collaboration between First Solar[1], AAA[2], Graco, Inc.[3], K-space[4], and Keyence[5]

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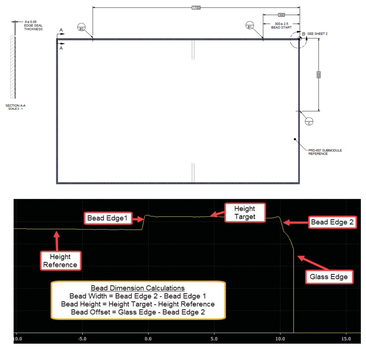
Edge Sealant Metrology

Edge sealant application dispense equipment and metrology

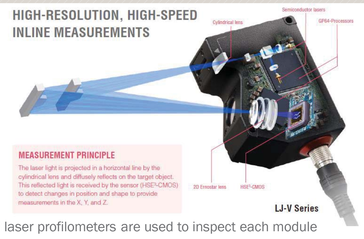


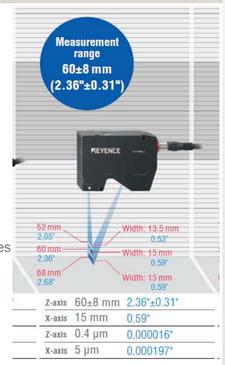
- First Solar's Series 6 glass/glass configuration utilizes an edge sealant to protect the active area from moisture and contamination
- New for Series 6, edge sealant is dispensed around the perimeter of the submodule with the desired dimensional control rather than applied as an extruded tape

2D Laser profilometer metrology was developed to inspect all dimensional parameters

- **Bead width** is measured by finding both bead edges
- **Bead offset** from edge is calculated based on the location of the bead edge relative to the glass edge
- **Bead height** is calculated based on using the active area as a height reference
- **Bead cross-sectional area** is calculated based on bead width and bead height measurements

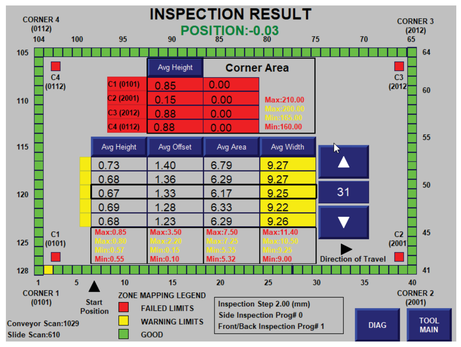
Edge sealant metrology laser profilometer technology





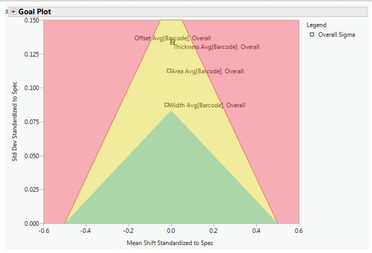
- 3 laser profilometers are used to inspect each module
  - 1 for each 2 meter edge and 1 moving profilometer for both 1.2 meter edges
- Keyence profilometer blue laser technology creates a surface profile of the edge seal bead in the X and Z directions. Sampling speed is up to 64kHz and position correction allows data capture during standard dynamic process conveyance.
- Corresponding Keyence controller allows real-time data transfer to PLC and SPC database. Separate controllers allow easy replacement of profilometers with minimal downtime.

Bead dimensional results are available on the HMI

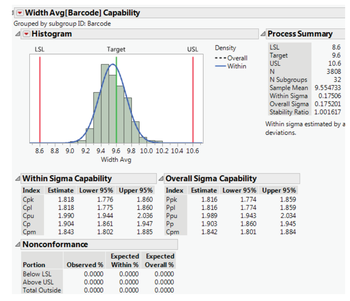


- Laser profilometer measurements occur every 2mm of edge seal bead
- Data are grouped into 128 50mm zones around the module perimeter for every module manufactured on the production line
- Average values are shown for each zone and color coded according to specification limits
- Detailed zone data can be seen by scrolling through each zone data set
- Corners have additional inspection technology involving a vision system, which is also shown on the inspection result HMI screen

Edge seal bead statistical process control

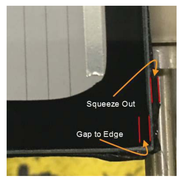


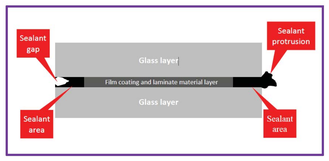
- An example of a summary chart for all 4 bead dimensions captured by the edge seal metrology showing mean shift on the X axis and standard deviation on the Y axis (left)
- An example of a more detailed process capability analysis for one dimension, in this case width (below, left)
- An example of more detailed inspection data including min and max data for each inspection zone and parameter that can be pulled directly from the PLC (below, right)
- Actual data were captured during equipment FAT



Edge Profiler Metrology

Panel edge profiler metrology

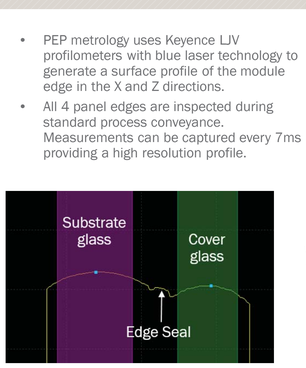


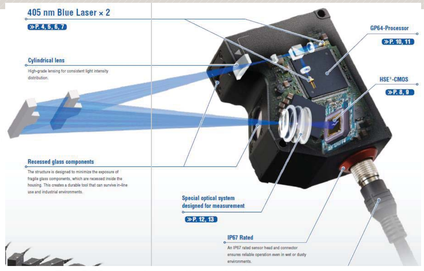


- During module lamination, a small amount of edge sealant squeeze-out may be produced due to the high pressure and high temperature process conditions. This is normal for lamination and an indicator of an adequate edge sealant to glass seal.
- To remove any excess edge sealant from the module perimeter, the module is exposed to an automated edge trimming process developed specifically for series 6.
- To achieve the best process control, First Solar and Kspace together developed the PEP laser metrology system for inspection after the trimming process to understand the quality of the trim process on a small scale.

PEP keyence laser profilometer technology

- PEP metrology uses Keyence LJV profilometers with blue laser technology to generate a surface profile of the module edge in the X and Z directions.
- All 4 panel edges are inspected during standard process conveyance. Measurements can be captured every 7ms providing a high resolution profile.

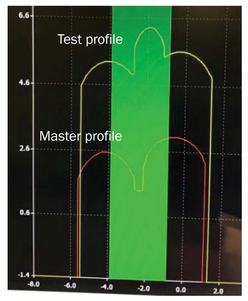




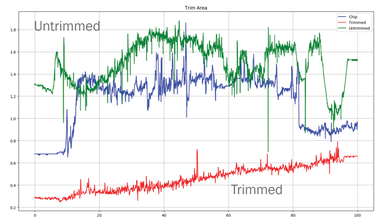
The PEP metrology collects the following outputs:

- Trim quality
- Module glass offset
- Module breakage
- Module chips

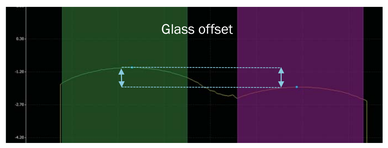
Pep output 1: module trim quality

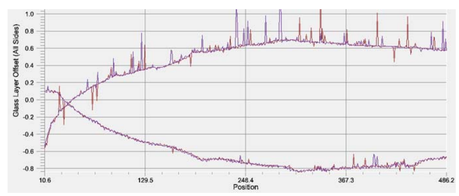


- The profilometers finds the module outer glass edges and sets a fixed distance to define the trim region
- The area of material in the trim region is calculated. This area is subtracted from a standard area generated with a master profile to define relative trim quality. An example of profilometer raw data is shown below
- The trim quality output provides process control for the trim process including triggering equipment maintenance and adjustments



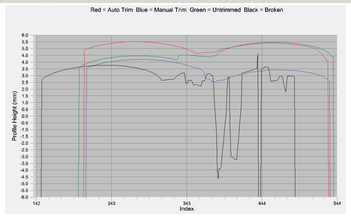
Pep output 2: module glass offset



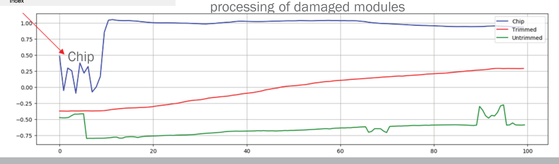


- The profilometer finds the maximum point of the glass edge radius for substrate and coverglass and calculates the difference in height
- Monitoring of glass offset allows for quick and easy process optimization upstream and assures product will be capable of frame application downstream
  - The PEP metrology also has the ability to capture the dimensions of the substrate and coverglass because profiles are generated for all 4 edges. These data can be used for incoming quality control.
  - The graph shown represents raw data from the profilometer for glass offset along the edges of one module. The overlay of 2 edges on the same graph shows offset is proportional as expected.

PEP output 3 & 4: module breakage and chips

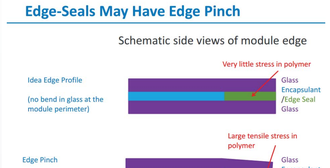


- The PEP metrology can capture module breakage and chips easily as they cause large deviations in the module edge profile as shown with the black profile (image on left)
- Breakage and chip detection resolution is <.2mm. Chips and breakage are easy to detect relative to the laser capability
- Below is an example of a module offset data plot for 3 modules showing one module with a chip.
- Detection of chips allows for quick correction of any chip or breakage inducing conditions on the manufacturing line and prevents additional processing of damaged modules



Edge Pinch Metrology

The importance of module edge pinch



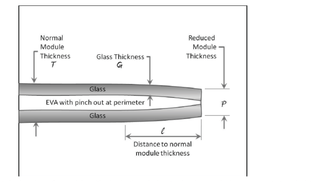


Fig. 2. Exaggerated edge-view of a module with "lamination punch-out" showing required measurements to calculate lamination stresses. Not to scale.

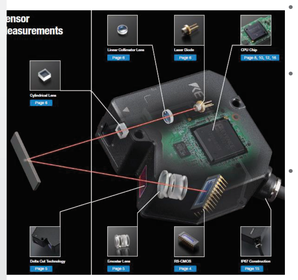
A simplified formula for calculating the approximate maximum bending stresses is provided below.

$$\text{Maximum stress in psi} = (T - P)(G)(2{,}600{,}000) / (\ell^2)$$

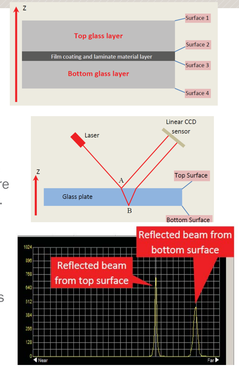
A lamination process that produces a module with the minimum amount of stress carried in the components is ideal. A simple and classic way to quantify lamination stress is by measuring edge pinch which is the difference in module thickness at the outer perimeter versus the inner body. Increased edge pinch means not only is the glass bent and more susceptible to failure, but the adhesive holding the pinched glass together is also under stress and more susceptible to delamination or cohesive failure. Simple calculations can be done to understand the stress induced in the glass based on edge pinch data (shown on right).

Sources: "Predicting the Performance of Edge Seal Materials for PV," 2012, Kempe, NREL/PR-5200-54582 and "Optimizing Photovoltaic Module Glass Reliability," Cording, SPIE Vol. 7048

PEP Keyence laser reflectance height sensor

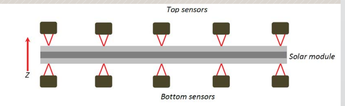


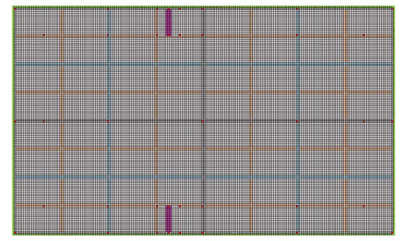
- The module is measured by a Keyence laser displacement sensor at 4 different surfaces (right)
- The Keyence LK-H052 sensor has a 20mm range and repeatability of +/-4 micron. Sensors will be mounted above and below the module to capture measurements from both sides.
- Images on the right show the principle of reflectance used to generate the distance of each surface from the sensor and subtract to determine module thickness. From these thickness measurements, module edge pinch is calculated.



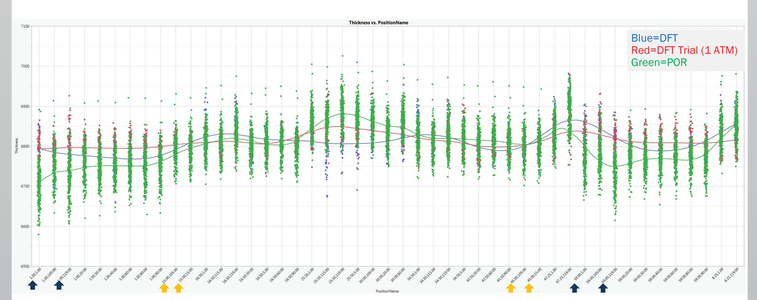
Edge pinch metrology measurement configuration

- 5 lasers are mounted above and below the module conveyor as shown to the right.
- Data are generated in 5 rows along the length of the module and module thickness and edge pinch are generated from a customized dialed-in selection of data points. S6 start-up measurement locations are shown below.





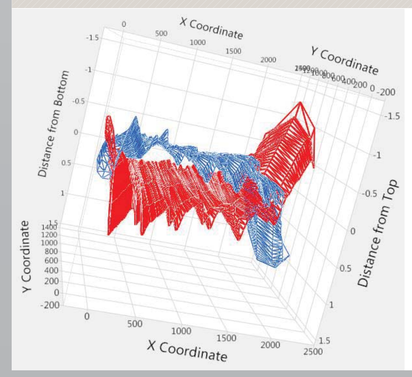
S6 shows an improved module thickness profile



Corners
Corner Reference

First Solar's new lamination technology produces less edge pinch and a more uniform module thickness profile indicating less stress contained in the package. (S6 lamination technology module thickness profile shown in blue and red, S4 technology shown in green).

Edge pinch metrology also captures module bow



- In addition to module thickness and edge pinch, the sensors capture the distance from the module to the sensor which allows a profile of module flatness to be generated. This information can be used for upstream process control and to assure tolerances are appropriate for roll coating processes downstream.
- The surface plot shows module profiles with module distance from the top sensor in blue and module distance from the bottom sensor in red.