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PV BACKSHEET FAILURE ANALYSIS BY SCANNING ACOUSTIC MICROSCOPY

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ABSTRACT: Photovoltaic module failure modes associated with backsheet degradation have a high relevance in the operation and maintenance of power plants. In this work, field-exposed modules are analyzed by Scanning Acoustic Microscopy (SAM) to visualize and localize backsheet failure modes in specific layers non-destructively. Acoustic micrographs were collected from material depths of the backsheet and allowed the visualization and assessment of depth profiles of the embedded PV module components individually. Multiple types of interlayer cracks were identified. These local defects of the backsheet were validated by microscopy images of destructively acquired backsheet cross-section samples. Additionally, the backsheet cracking are reproduced in laboratory under UV-DH combined aging test.
Keywords: Backsheet cracking, scanning acoustic microscopy, field-exposed PV modules, dry-UV aging, UV-DH combined aging

1 INTRODUCTION

Backsheet cracks have been recently identified as a one of the major causes of defects in PV modules [1]. Typical degradation patterns start with a loss of mechanical and thermal stability, electrical insulation and prevention from moisture and gas ingress. Because of the diversity of requirements a backsheet must fulfill, they are usually composed of different layers, each of them performing specific functions such as electrical insulation, protection and moisture and gas ingress. It has been reported that several field-exposed PV modules were affected by backsheet degradation within the polymeric layers. For examples, the presence of severe cracks like in the protective polyamide (PA) layer in the PET-based backsheets or with the degrease in the insolation resistance like in the PET-PP based backsheets [2]. More recently, the multilayer polyamide composites known as AAA backsheet have shown sever failures due to cracking, delamination or photo-degradation of the outer PA surface [3]. Furthermore, the degradation of AAA has resulted in the photo-degradation of the neighboring EVA encapsulant during a combined UV-DH accelerated aging test [4].

The need for new testing and benchmarking methods that allow a comparison and selection of PV components, especially backsheets has been highlighted [5]. Because currently a failure analysis requires extensive destructive sample preparation in order to visualize all the layers, there exists great interest in fast and non-destructive methods for identifying and localizing backsheet failures in PV modules. A recent method of backsheet cracking propensity quantification has been developed by combining accelerated weathering with in situ surface cracking monitoring during tensile deformation [6]. This is so far the only method that can quantify backsheet cracks, but it is unable to detect defects inside the material stack.

The Scanning Acoustic Microscopy (SAM) (Figure 1) is a non-destructive technique that offers the possibility of analyzing the of PV module components because it can provide real-time acoustic high spatial resolution information from the internal structure of materials, for example, the longitudinal modulus of backsheet and encapsulant foils. It was shown that the determined longitudinal modulus of backsheet and encapsulant has a good correlation with the Young's modulus calculated from the tensile tests [7]. In terms of imaging, it was reported that SAM delivers complementary information to electroluminescence and dark lock-in Thermography on the quality of PV modules [8].

This study demonstrates the application of SAM for the evaluation of PV backsheet degradation upon weathering. Towards this goal, degraded backsheets of different layer structure were analyzed by SAM to understand and localize failure modes such as cracks in specific layers that are otherwise not assessable without destroying the module. The SAM results are validated by microscopy images of destructively acquired backsheet cross-section samples. Finally, a comparison of backsheet degradation between Field-aged and laboratory-aged PV modules is performed.

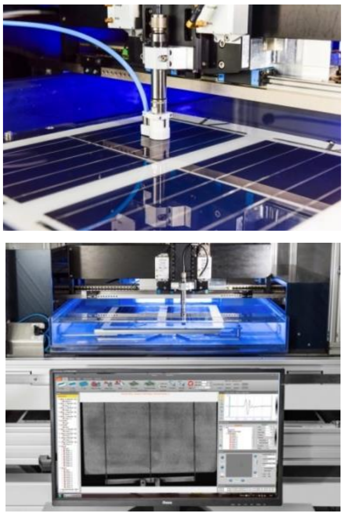

Figure 1 Top: Photograph of PV module being scanned from the front side by SAM. Bottom: Photograph of a PV module sample with the transducer being immersed in during SAM measurement.

2 EXPERIMENTAL

2.1 Field-exposed PV modules

Two PV modules from different power plants, exhibiting features that suggest an advanced stage of backsheet degradation, were analyzed and compared:

- Case 1: Field aged PV module with damaged white PP inner backsheet layer
- Case 2: Field aged PV module with backsheet cracking between the cells and backsheet chalking

To confirm the observations from SAM imaging, samples of backsheets were carefully extracted from the rear side in between the cells and embedded in epoxy resin, ground and polished to allow subsequent analysis of the backsheet cross sections with a Olympus reflected-light microscope.

2.2 Laboratory-aged PV mini-modules

Two identical one-cell mini-modules (20 x 20 cm²) were prepared by laminating a layer of PA-based backsheet (AAA) and 2 layers of ethylene vinyl acetate (EVA) sandwiching a monocrystalline silicon cell on a transparent glass cover. The samples were then subjected to two different indoor accelerated aging conditions (1) 240 kWh/m^2 dry-UV irradiation according to IEC61215-2:2016. And (2) a combined UV-DH (air 60 °C/85% RH) test with the UV irradiation is comparable to the dry UV test.

2.3 Scanning Acoustic Microscopy

The PV modules were placed flat into a water tank and scanned by a SAM HD² (PVA TePla Systems GmbH) using a 15 MHz transducer for the fielded modules and a 30 MHz transducer for the laboratory aged mini-modules at ambient conditions. The PV modules were analyzed through the backsheet and the interpretation of the acoustic signals generated due to the impedance mismatch between interfaces was performed based on the knowledge of the existing layers on the PV modules. Acoustic images were generated by scanning over the gates describing the echoes in a reflectogram which is represented as the travel time of the acoustic wave into the material as called the time-of-flight (TOF).

3 RESULTS AND DISCUSSION

3.1 Analysis of degraded backsheet from field-exposed full-size modules

The microscopic images showed in **Fehler! Verweisquelle konnte nicht gefunden werden.** represent the backsheet cross sections of the modules case 1 and case 2 as described earlier.

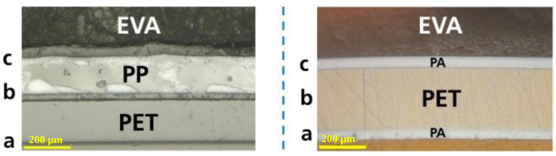

Figure 2 Microscopic images of Backsheets cross-sections. The letters a, b and c indicate the interfaces shown in the SAM images (Fig. 5, 6). Case 1 (left): destroyed PP inner layer; Case 2 (right): Cracks in outer PA layer.

The acoustic micrographs in Figure 3 were generated from specific gates in the reflectogram, representing different depths inside the fielded PV module. This is desired if individual interfaces between the PV components are inspected. For example, using one SAM scan, three micrographs can be generated: (top image) Backsheet/encapsulant interface, (middle image) ribbons of the backside of the cells. Therefore, the image looks darker and (bottom image) encapsulant/cells interface. Here, the ribbons and silver pads at both sides of the cells are visible.

Figure 3 Acoustic micrographs (SAM images) generated from the different spectral regions (“gates”) from a full-size module.

The backsheet of the Module case 1 could be identified to consist of a fluoropolymer coating (outer layer), polyethylene terephthalate (PET) (core layer) and a damaged polypropylene (PP) (inner layer) as shown in **Fehler! Verweisquelle konnte nicht gefunden werden.**. This backsheet had previously been inspected visually and no BS-cracking had been observed of the module.

Figure 4 represents the reflecrtogram of the PV module (case 1) measured from the rear side (BS) in the intercellular gaps. The acoustic beam is focused at the BS surface (first peak on the left). The assignment of the signals was done based on the knowledge on the present interfaces in the module [8]. The strongest peak on the left at 2.65 µs TOF corresponds to the water/BS surface (outer layer in green in Figure 4), the following gates are assumed to correspond to the core/inner layers interface (orange) and the inner/encapsulant interface (red).

As observed in the visual inspection, the weathered backsheet outer layer has an intact surface (echo (a) Figure 6) between and behind the cells. Inside the backsheet and only between cells, cracks in one direction are observed at the core/inner layers interface (echo (b) Figure 6). Deeper inside the inner layer, additional smaller cracks in multiple directions are visible (echo (c) Figure 6).

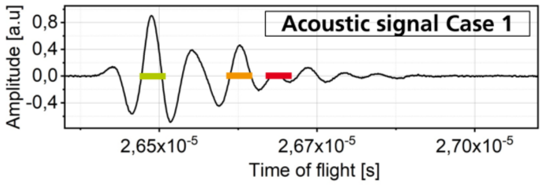

Figure 4 TOF-amplitude reflectogram of a PV module case 1

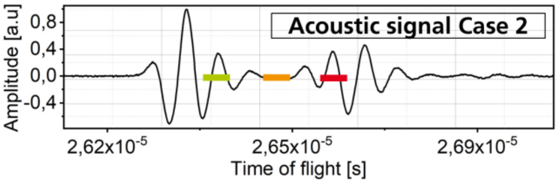

Figure 5 TOF-amplitude reflectogram of a PV module case 2

The second type (case 2) of the PV-field aged module (**Fehler! Verweisquelle konnte nicht gefunden werden.**) contained a backsheet consisting of a PET core layer sandwiched by two PA layers. By placing three gates in reflectogram in Figure 5, the acoustic images in the Figure 7 were obtained at specific corresponding acoustic depths inside the multilayered backsheet. At the outer PA/core PET layers interface, both cracks in the machine direction can be observed. These are especially pronounced in the cell gap locations, where additional, smaller cracks in different directions are present (echo (a) Figure 7). All cracks are difficult to see with the naked eye (almost not visible). The corresponding acoustic image of echo (b) Figure 7 shows larger cracks in a gate (b) that is assigned to the bulk of the PET core layer. The cracks appear with high contrast since no interface was detected in this region (no peak reflectogram, Figure 5). The last image at echo c, Figure 7, represents the core/inner layers interface.

Both cases of backsheet cracking presented earlier are observed only along the intercellular spacing where the front UV irradiation can be absorbed during operation. The structure of these cracks can be clearly visualized and quantified by SAM analysis. In case 2 both cracking types mainly affect the outer PA layer and the Inner PET layer. However in case 1, both crack types are visible at the inner/EVA layer interface. In a previous study, similar cracks were accompanied by a delamination of the inner PA-layer from one of the adjacent layers[3].

3.1 Laboratory-produced backsheet cracking (one cell mini-modules)

The AAA backsheet was used for the production mini-modules. As discussed, this type of backsheet is known to show outer layer cracks in the field. This type of degradation was not detected after the application of dry UV aging for 240 kWh/m^2.

However, outer layer field cracks, similar to case 2, were obtained after a 240 kWh/m^2 UV irradiation; elevated temperature and elevated relative humidity were combined in the aging tests (UV/DH). This acknowledges that moisture plays a synergistic role with UV in the formation of surface backsheet cracking [4,6]. The same failures have been also recently reproduced by an indoor accelerated aging test utilizing simultaneous combined stresses (UV, humidity, temperature and

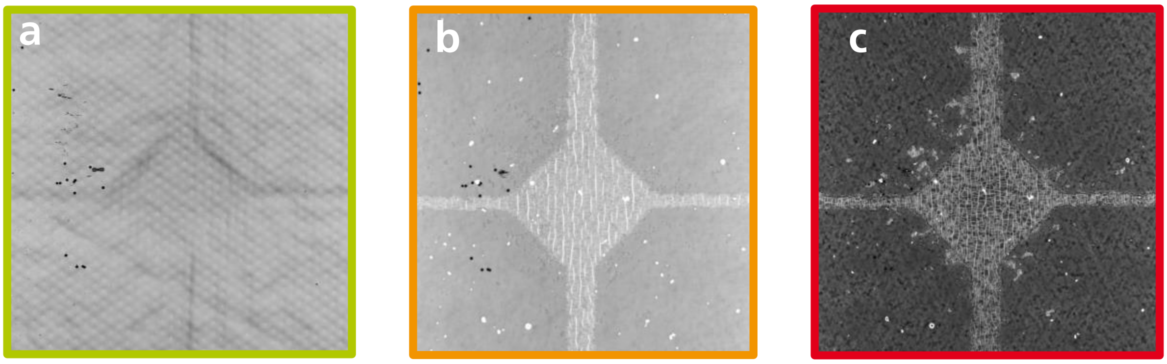

Figure 6 SAM images of Case 1: a. outer layer surface; b. core/inner layers interface; c. inner layer bulk

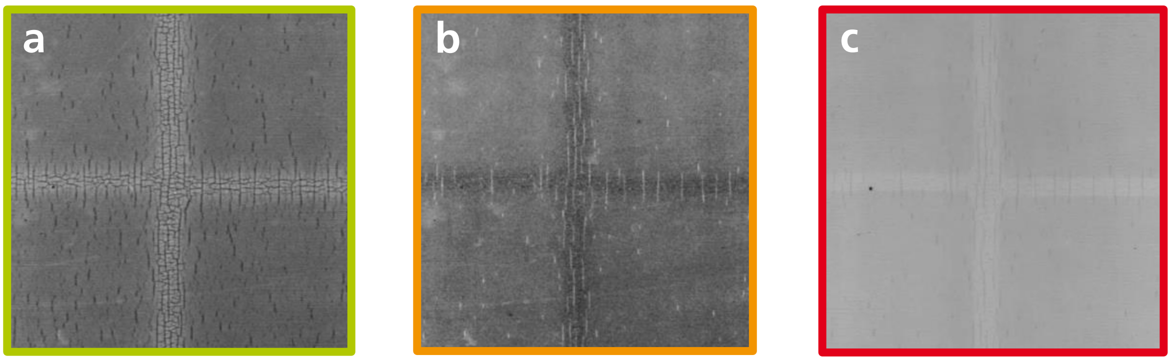

Figure 7 SAM images of Case 2: a. outer/core layers interface; b. core layer bulk; c. core/inner layer interface

thermo-mechanical load) [9].

Acoustic images in the Figure 8 were taken by applying gates to peaks (#1) and (#2) as indicated in Figure 9, before and after a UV/DH combined accelerated aging test. The acoustic beam can be focused to increase the amplitude of specific signals and thereby increase the image quality for a chosen interface. The images at echo #2 show the main elements at the back surface of the cell, such as the back ribbons and cross-connector. Naked eye visual and additional non-visual cracks (orange arrows) are detected with SAM image after the aging test.

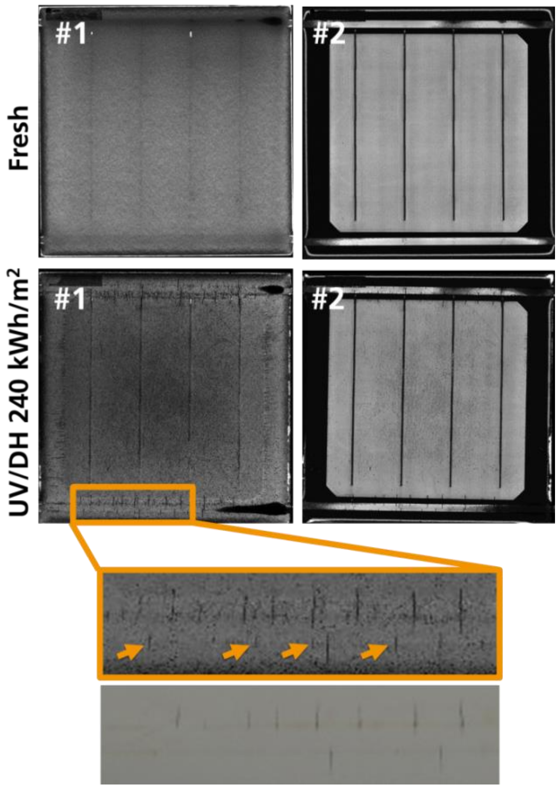

Figure 8 Acoustic micrographs of mini-module 2 before (top) and after UV/DH combined aging test (bottom) at the BS (#1) (left) and cell interface (#2) (right)

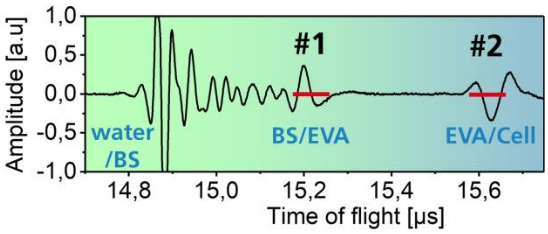

Figure 9 TOF-amplitude reflectogram of a PV mini-module measured at 30 MHz

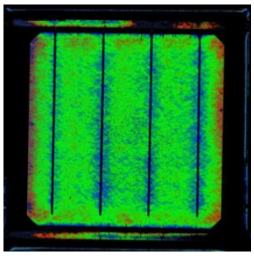

Figure 10 Time of flight (TOF) from water/BS to EVA/Cell interfaces. **Red** (short) to **blue** (long) shows different polymer thickness

An additional feature of SAM is the visualization of layer thickness. Figure 10 shows an acoustic measurement from the water/BS to EVA/Cell interfaces, recorded, where the colors represent the depth information in combination with the speed of sound. Specifically, blue corresponds to a long TOF, green is shown when the TOF is shorter and red corresponds to the shortest TOF. With the TOF being proportional to the thickness of a given homogeneous material, this image reveals details on the backsheet and EVA thickness inhomogeneities due to the arrangement of other module components, such as the cross-interconnects at the top and bottom edges of the module, the rear side ribbons, and the cell boundaries.

4 CONCLUSIONS

In this work we demonstrated that SAM can uncover backsheet cracking in specific interlayers non-destructively, as validated with conventional destructive tests. Various types of BS cracking were locally distinguished and quantified in the intercellular gap for the field degraded PV modules under the acoustic micrographs. Furthermore, similar backsheet cracks were reproduced in the laboratory under UV/DH combined conditions, whereas, the cracks were absent by the conventional dry-UV test. Additionally, SAM proved to be a useful technique to detect backsheet cracks that are otherwise not detectable in the visual inspection. The depth profile analysis indicated that SAM can be applied to detect thickness homogeneities within the backsheet and encapsulant layers.

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