4th Atlas/NIST Workshop on Photovoltaic Materials Durability

Fragmentation test for crack propensity evaluation of PV backsheets

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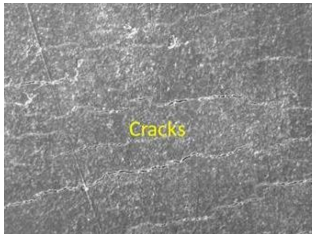
Backsheet cracking in the field modules

*Microcracks in polyamide backsheet (Western China)



**Hairline cracks in polyamide backsheet (China, humid subtropical)

- Various sizes in backsheets

***Cracks in polyester based backsheet (Eastern Spain)

*Felder et al. SPIE (2014), **Fairbrother et al. SPIE (2017), ***Gambogi et al. EUPVSC (2013)

Backsheet cracking from Indoor and outdoor tests

Outdoor

Field modules	• Yellowing • Cracking of Outer layer • Delamination of Outer layer

- Backsheet cracking in field modules
  - ✓ Loss of physical protection
  - ✓ Electrical insulation

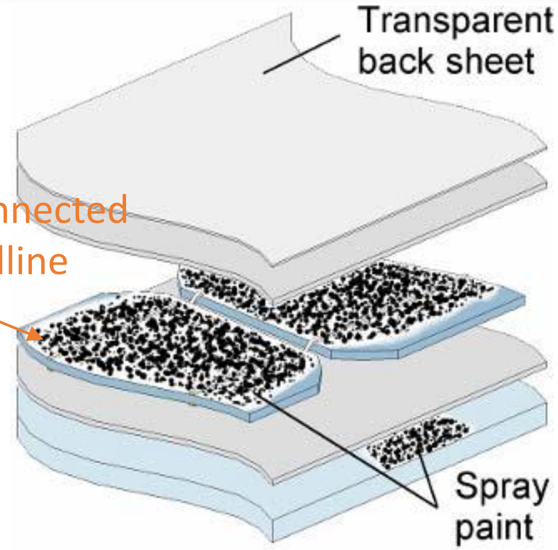
Indoor

UV exposure of backsheet	• Yellowing
Damp Heat of backsheet	• Yellowing
Damp Heat of modules	• Cracking
UV/Thermal cycling of modules	• Yellowing • Cracking

- Backsheet cracking within the modules in hot environment

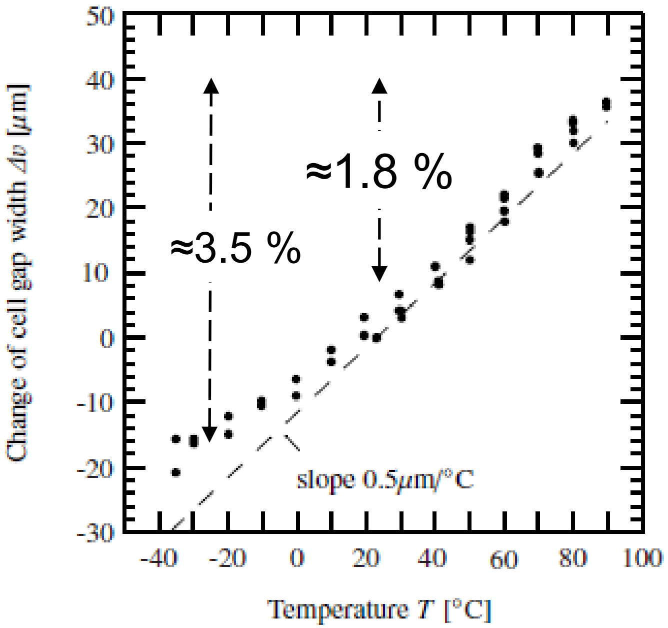
Gambogi et al. IEEE J. Photovoltaics, 935 (2014)

*Strain level for cell gap width during thermo-Mechanical Test of PV Modules



Cell gap distance = 2 mm

Temp. cycle based on IEC 61215



- Apparent small strain (2 % to 4 %) for a PV module

*U. Eitner et al. (2011) Book chapter in Shell-like structures

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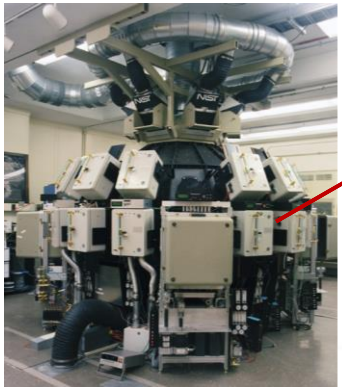
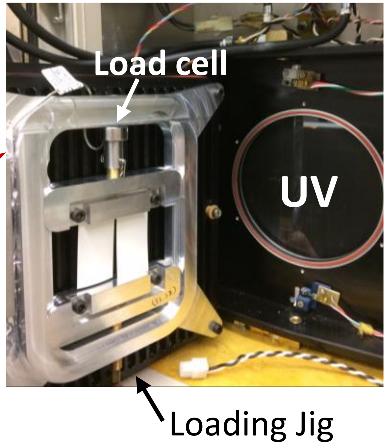
Key research objectives

- Develop test methodology to understand cracking behaviors for PV backsheets, and extend to address backsheet failure in field PV modules
  - ✓ First step: Measuring crack formation in accelerated test conditions (time, temperature, mechanical elongation)

Accelerated tests (UV, Humidity, Temp.) With mechanical stress

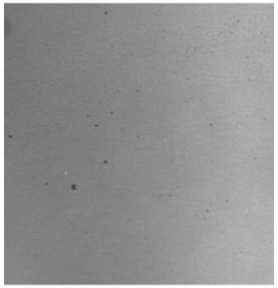
With mechanical stress **simultaneously**



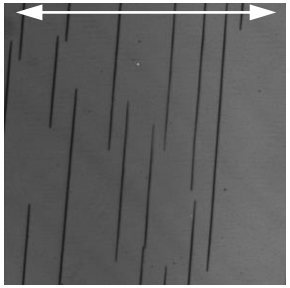


- UV exposure under mechanical stress

UV exposed PET film at 23 °C (Confocal microscopy)



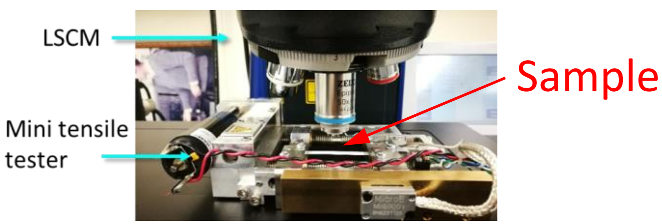
Without tension



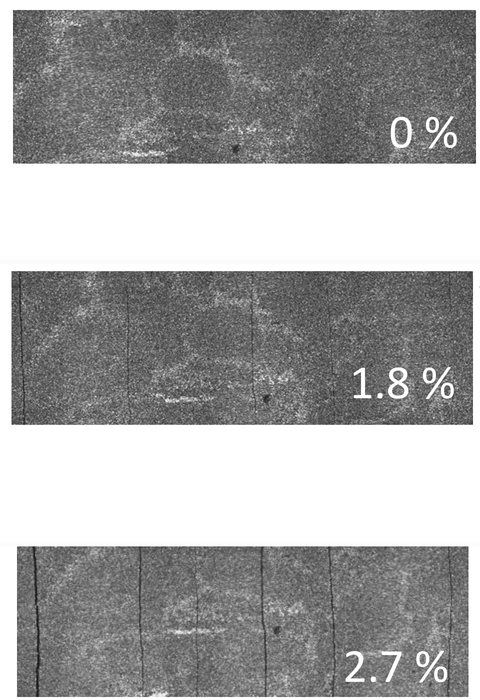
With tension (≈2 % strain)

Accelerated tests (UV, Humidity, Temp.) With mechanical stress (*continued*)

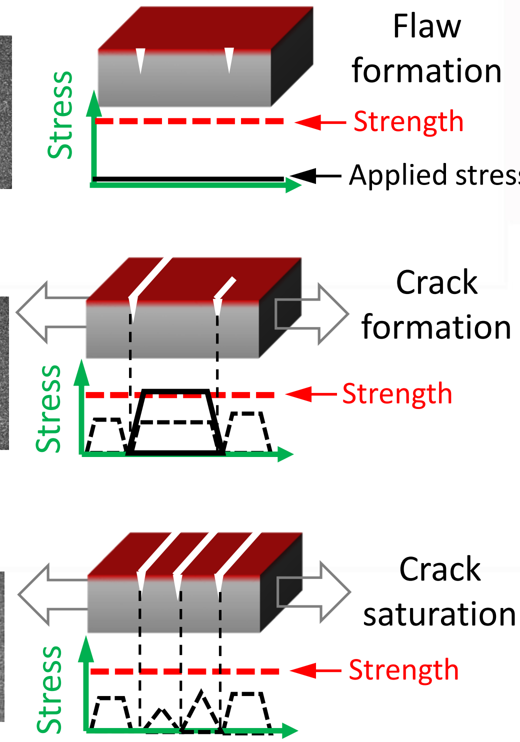
With mechanical stress **sequentially** (Fragmentation test)



Crack images



Illustrations



Experimental conditions

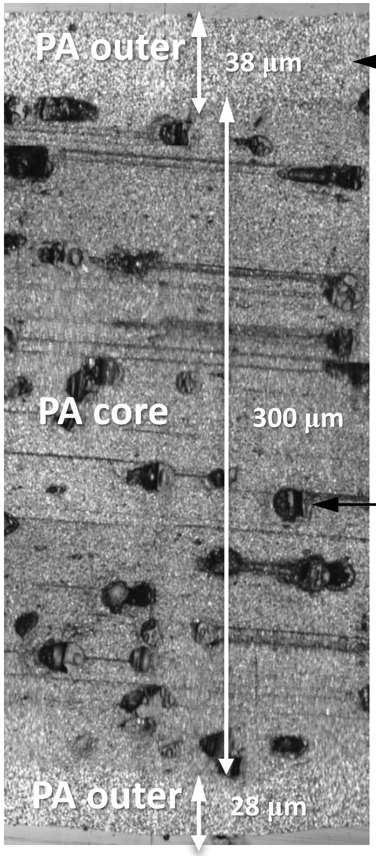
Material:
Polyamide backsheet

Aging conditions:
Xenon arc with 65 °C/20%RH
for 250 h, 500 h, 1000 h, 2000 h, 4000 h

Mechanical measurements:
- **Fragmentation test for backsheet**
- AFM (DMT modulus)

Spectroscopic measurements:
- FT-IR (oxidation index)
- Fluorescence (visual inspection)

Cross-section



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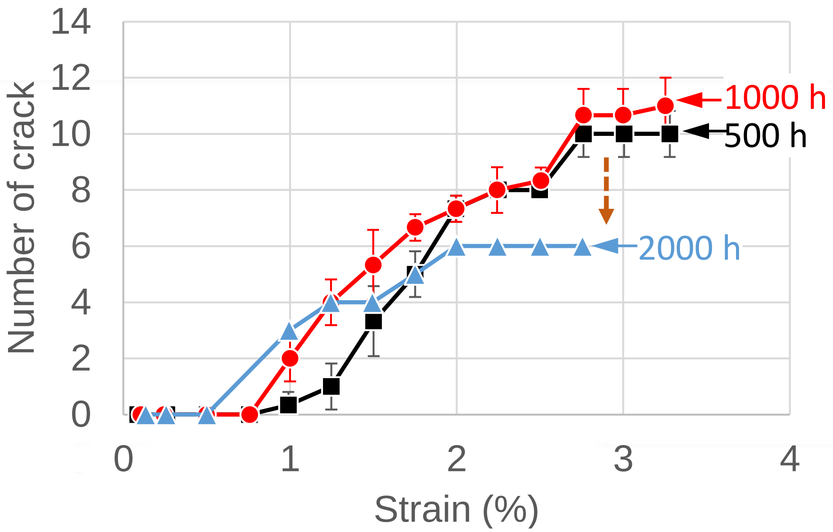
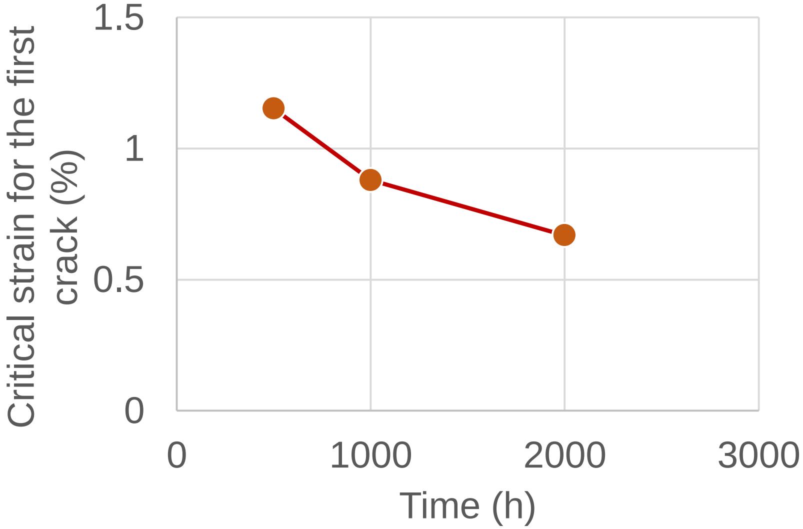
Fragmentation test results for UV exposed Polyamide backsheets



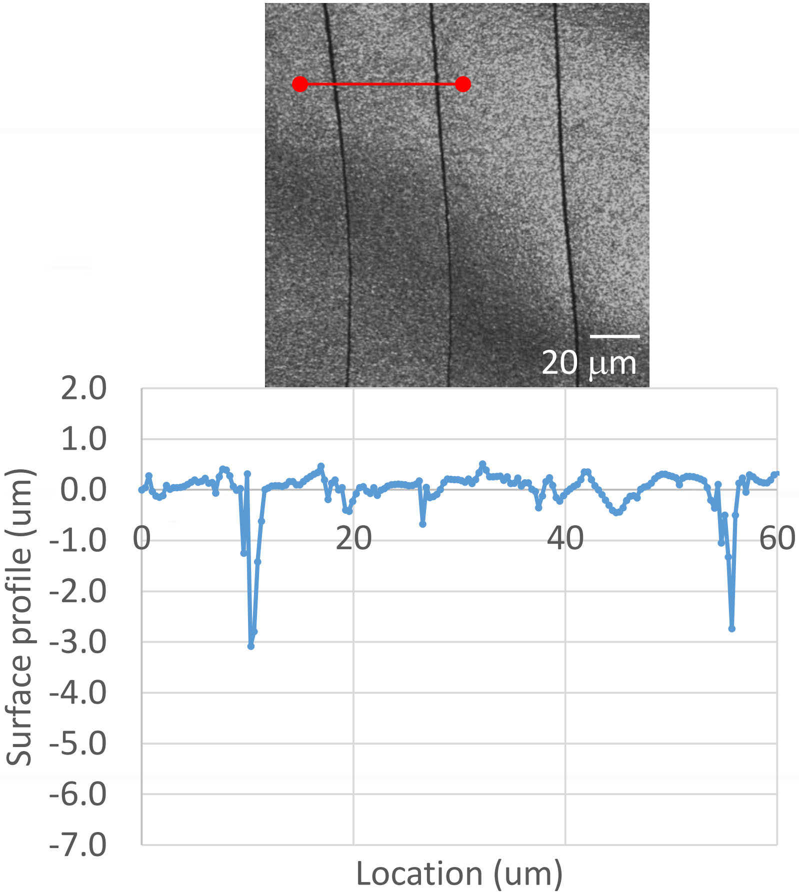
- Lower number of cracks for the 2000 h sample at the saturation strain compared to 500 h and 1000 h samples



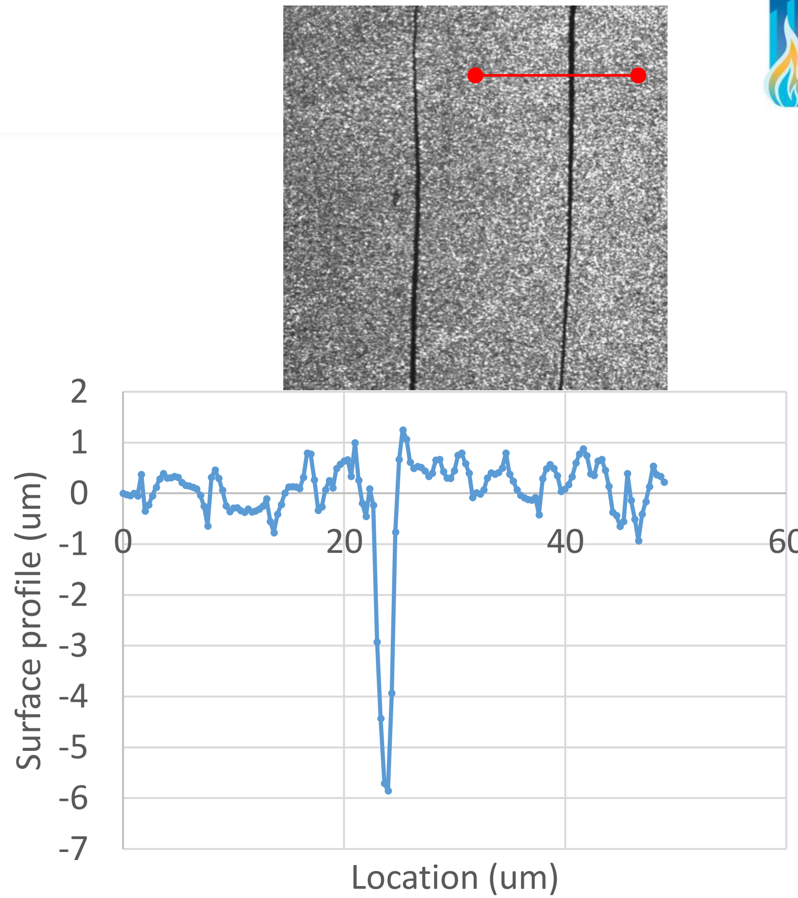
- Lower critical strain (the first crack formation) for the 2000 h sample compared to the 500 h and 1000 h samples

Crack depths in PA backsheets after fragmentation tests

500 h



2000 h



- Narrow and shallow cracks
- Wide and deeper cracks

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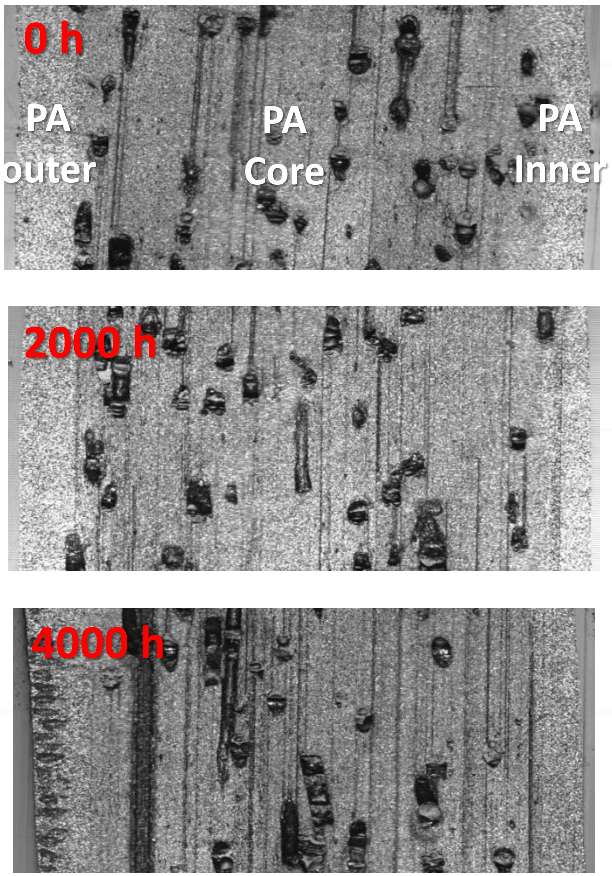
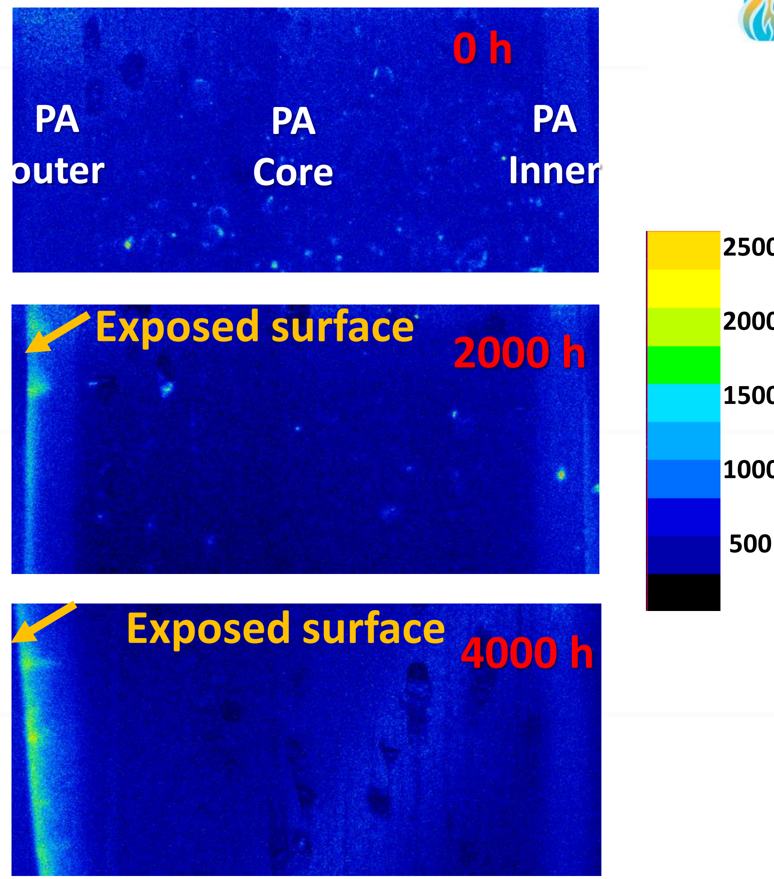
Depth profiles in the cross-section of Polyamide backsheets

Confocal microscopic images

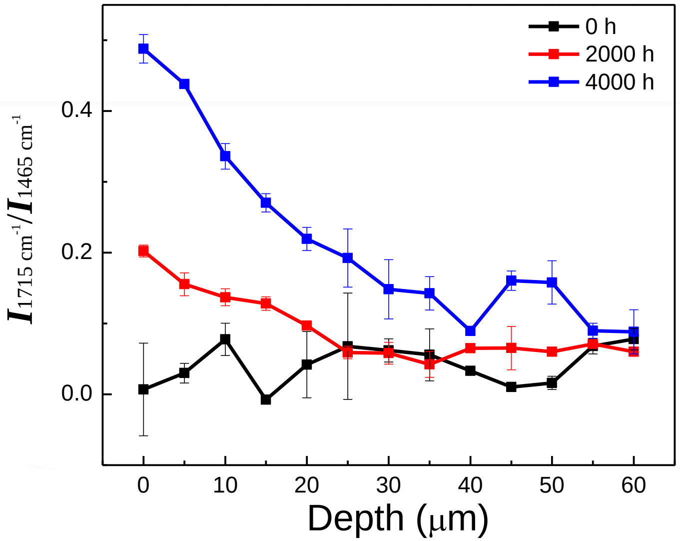


Fluorescence images

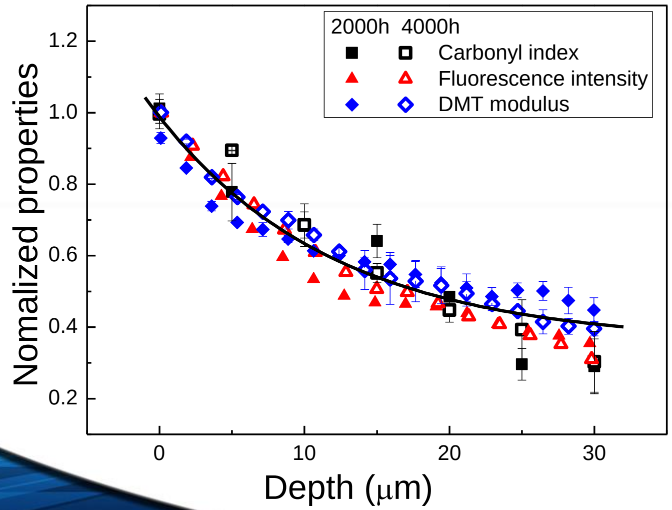


- Spectral changes of fluorescence on the exposed surfaces become deeper with times (i.e. deeper crack)

Depth profiles in the cross-section of Polyamide backsheets (Oxidation & Stiffness)



- Higher oxidation on the exposed sides of the cross-sections (suggesting chain scissions)



For the UV exposed side of the cross-sections,

- Higher oxidation
- Higher fluorescence intensity
- Higher modulus

Similar oxygen diffusion rates between 2000 h and 4000 h

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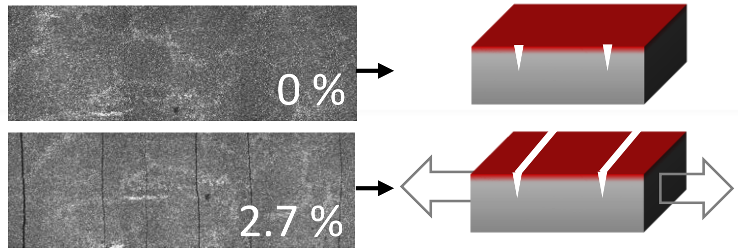
Using fragmentation data for polyamide backsheets (**Strength** and **Crack density** for degraded layer

Confocal microscope images



Film strength (σ_{str}) in film/substrate systems

$$\sigma_{str} = \frac{E_f}{(1-\nu_f)}\left[\frac{(1-\nu_f \nu_s)\varepsilon_c}{(1+\nu_f)}\right]$$

E_f : Film modulus, ν_f: Poisson ratio of film
ν_f :Poisson ratio of substrate
ε_c : Critical strain (strain for the first crack)

Crack density at a strain in film/substrate systems

$$\frac{\varepsilon_a}{\varepsilon_c} = \sqrt{\frac{3}{2R}}$$

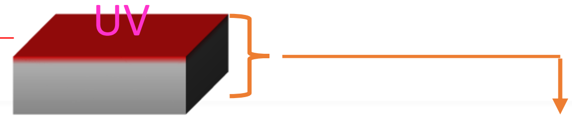
$$R = 4\tanh\left(\frac{\alpha l}{2}\right) - \frac{e^{\alpha l} - e^{-\alpha l} + 2\alpha l}{e^{\alpha l} + e^{-\alpha l} + 2} - 2\tanh(\alpha l) + \frac{1}{2}\frac{e^{2\alpha l} - e^{-2\alpha l} + 4\alpha l}{e^{2\alpha l} + e^{-2\alpha l} + 2}$$

Where, $\alpha l = \left[\frac{2}{3\beta(1+\nu_s)}\left(\frac{1}{\beta} + \frac{(1-\nu_f^2)E_s}{(1-\nu_f \nu_s)E_f}\right)\right]^{1/2} \times \frac{\bar{l}}{t}$ and $\beta = \frac{s}{t}$

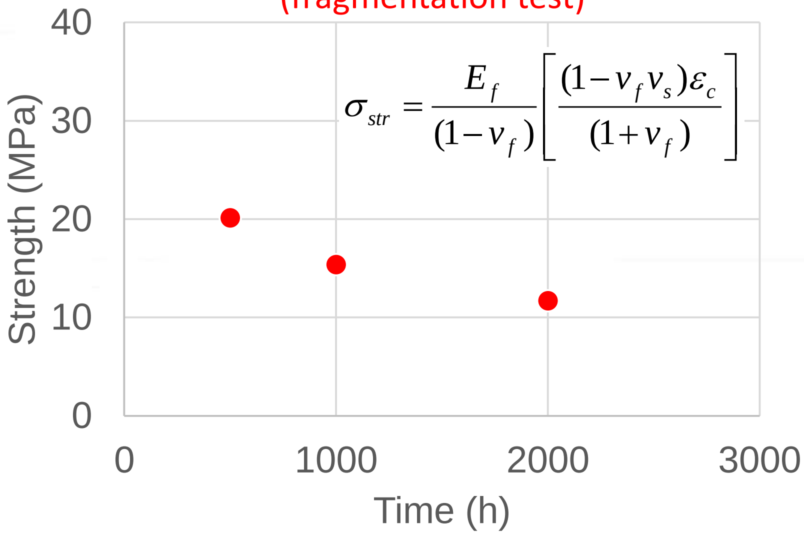
t: thickness of the exposed layer
s: effective substrate thickness
ε_c : Critical strain (strain for the first crack)
$\bar{l}$: average space between the cracks

[Hsueh and Yanaka, J. Mater. Sci. pp1809 (2003)]

Using fragmentation data for polyamide backsheets (**Strength** for degraded layer)

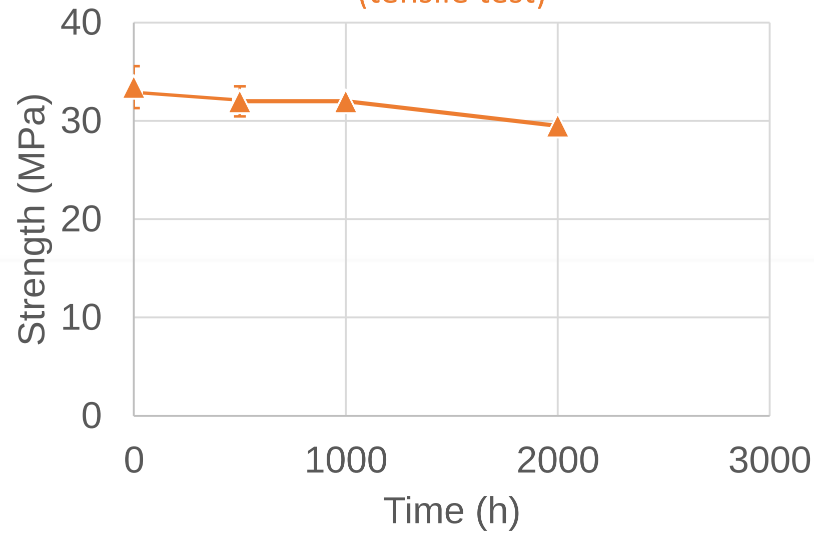


Strength of the exposed surface (fragmentation test)



$$\sigma_{str} = \frac{E_f}{(1-v_f)}\left[\frac{(1-v_f v_s)\varepsilon_c}{(1+v_f)}\right]$$

Measured backsheet strength (tensile test)



- Lower strengths than the bulk backsheet strengths
- Strength reductions on the exposed surface compared to the bulk backsheet strengths

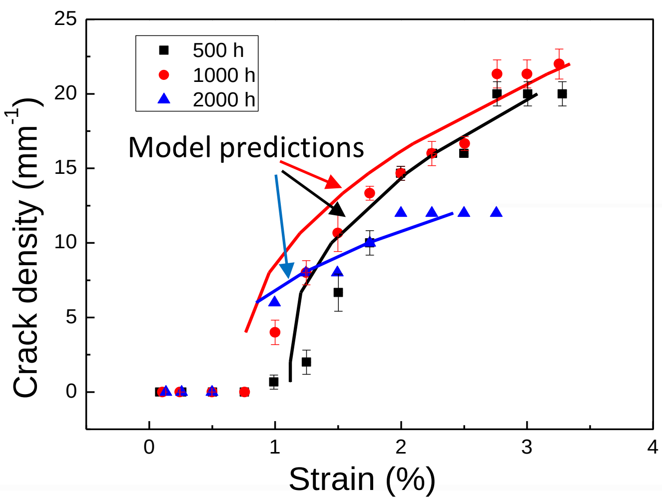
- No significant change for the bulk backsheet strengths

Applications of fragmentation data for polyamide backsheets (**Crack density** predictions for degraded layer)

$$\frac{\varepsilon_a}{\varepsilon_c} = \sqrt{\frac{3}{2R}}$$

$$R = 4\tanh\left(\frac{\alpha l}{2}\right) - \frac{e^{\alpha l} - e^{-\alpha l} + 2\alpha l}{e^{\alpha l} + e^{-\alpha l} + 2} - 2\tanh(\alpha l) + \frac{1}{2}\frac{e^{2\alpha l} - e^{-2\alpha l} + 4\alpha l}{e^{2\alpha l} + e^{-2\alpha l} + 2}$$

Where, $\alpha l = \left[\frac{2}{3\beta(1+v_s)}\left(\frac{1}{\beta} + \frac{(1-v_f^2)E_s}{(1-v_f v_s)E_f}\right)\right]^{1/2} \times \frac{\bar{l}}{t}$ and $\beta = \frac{s}{t}$



- Measured crack densities ≈ Predicted crack densities
- Lower crack density for the 2000 h sample (possibly due to deeper crack formations through the thickness)

Summary

- Critical strains of the polyamide backsheets showing the first cracks decreased with increasing the exposure times
- Strengths and crack densities of the exposed surface layers decreased with increasing the exposure times
- Highest oxidation indexes, fluorescence intensities, and modulus on the exposed sides were observed, and gradually decreased with the thickness of the depth

Thank you !

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