Fragmentation Test for Assessing Photovoltaic (PV) Backsheet Cracking Propensity

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(DuraMAT-SPARKS)

A Novel Method to Evaluate Crack Propensity of PV Backsheets

NIST/UL Workshop for PV Materials Durability
Gaithersburg, MD 20899
December 12-13, 2019

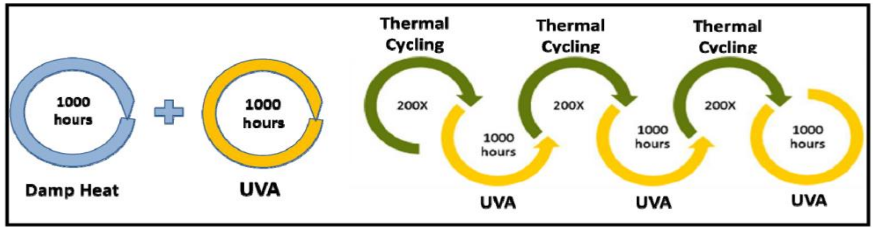
Rationale: to Reproduce and Understand the Field Backsheet Cracking

- **Backsheets tend to fail by:**
  - Loss of electrical insulation
  - Burn through by arcing or extreme heating
  - Delamination
  - Cracking

Michael D. Kempe, Xiaohong Gu, Yadong Lyu, Jae Hyun Kim, Ben Foltz and Thomas Felder, "A novel method to evaluate the crack propensity of PV backsheets," PVRW 2019, Denver, CO

Cracking in Fielded Backsheets

- In the 2010 to 2012 timeframe, many modules were deployed containing a polyamide based backsheet (AAA) presented dramatic cracking failure in as little as 4 years despite passing IEC 61215.
- Some PPE and PVDF backsheets also failed with cracks in the machine direction preferentially along busbar ribbons.
- **There is a need to develop methods to understand, characterize and prevent this failure mode.**
- *DuPont MAST; NREL Combined-Accelerated Stress Testing (CAST) test; Solder Bump Coupon Testing of Backsheets, etc.*

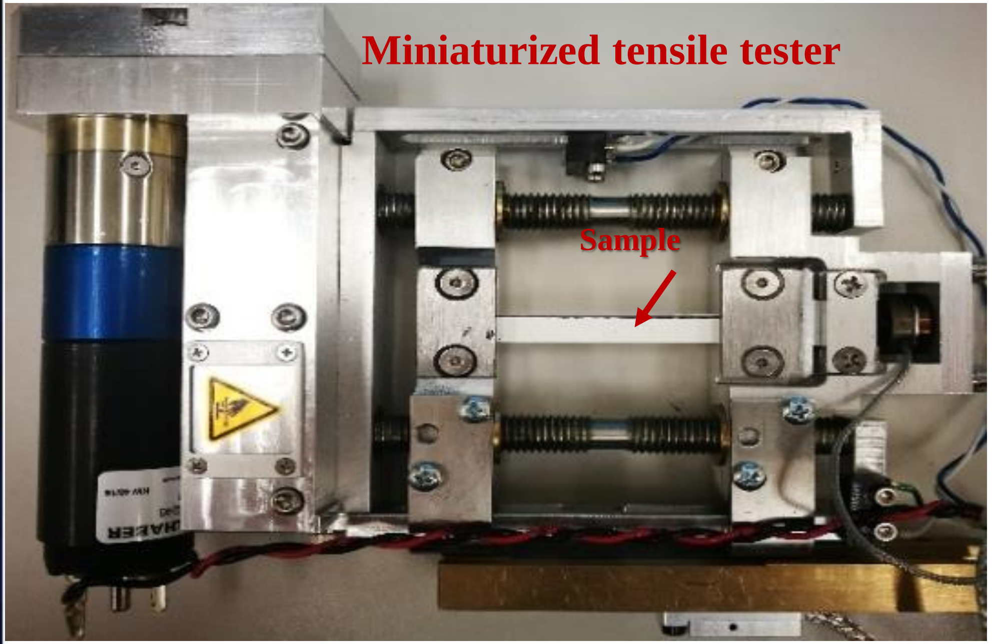


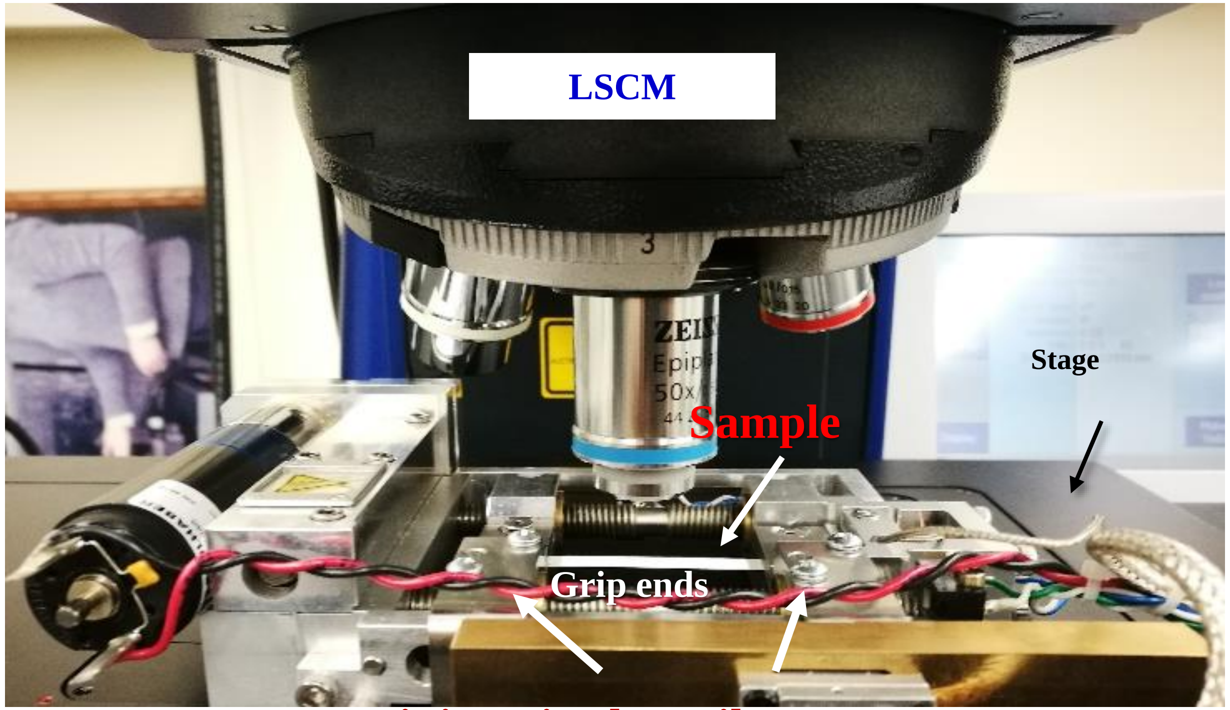
➢ ***To further develop a simple and semi-quantitative material test method to replicate, early-detect, and predict the cracking propensity of backsheets.***

Channel Cracking Fragmentation Testing

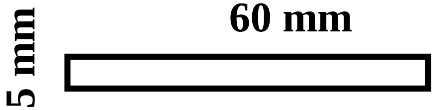
- Laser scanning confocal microscope (LSCM) + Displacement controlled tensile fixture

LSCM can be replaced by other types of microscopes (optical, SEM, AFM) for imaging the fragmentation processes





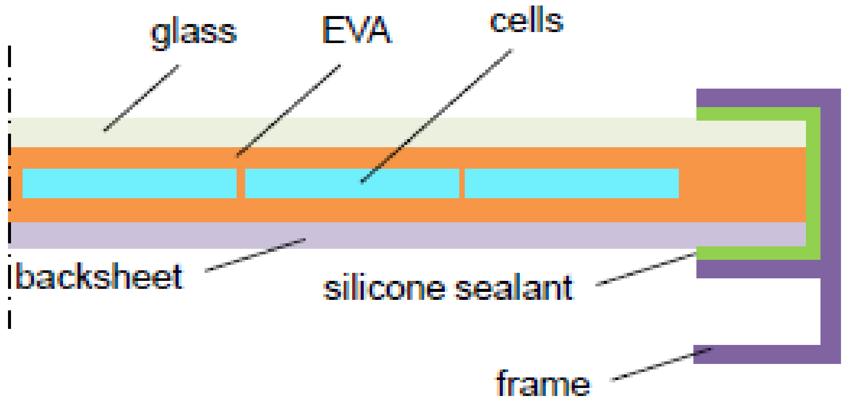
Miniaturized tensile tester



Gauge length: 35 mm

- In-situ monitoring surface morphology while applying small controlled strains on the sample.
- Simultaneous load-displacement curves with confocal images.
- Samples are free-standing films.

Thermo-mechanical Stress in PV Modules Induced by Coefficients of Thermal Expansion (CTE) Mismatch of Different Module Components



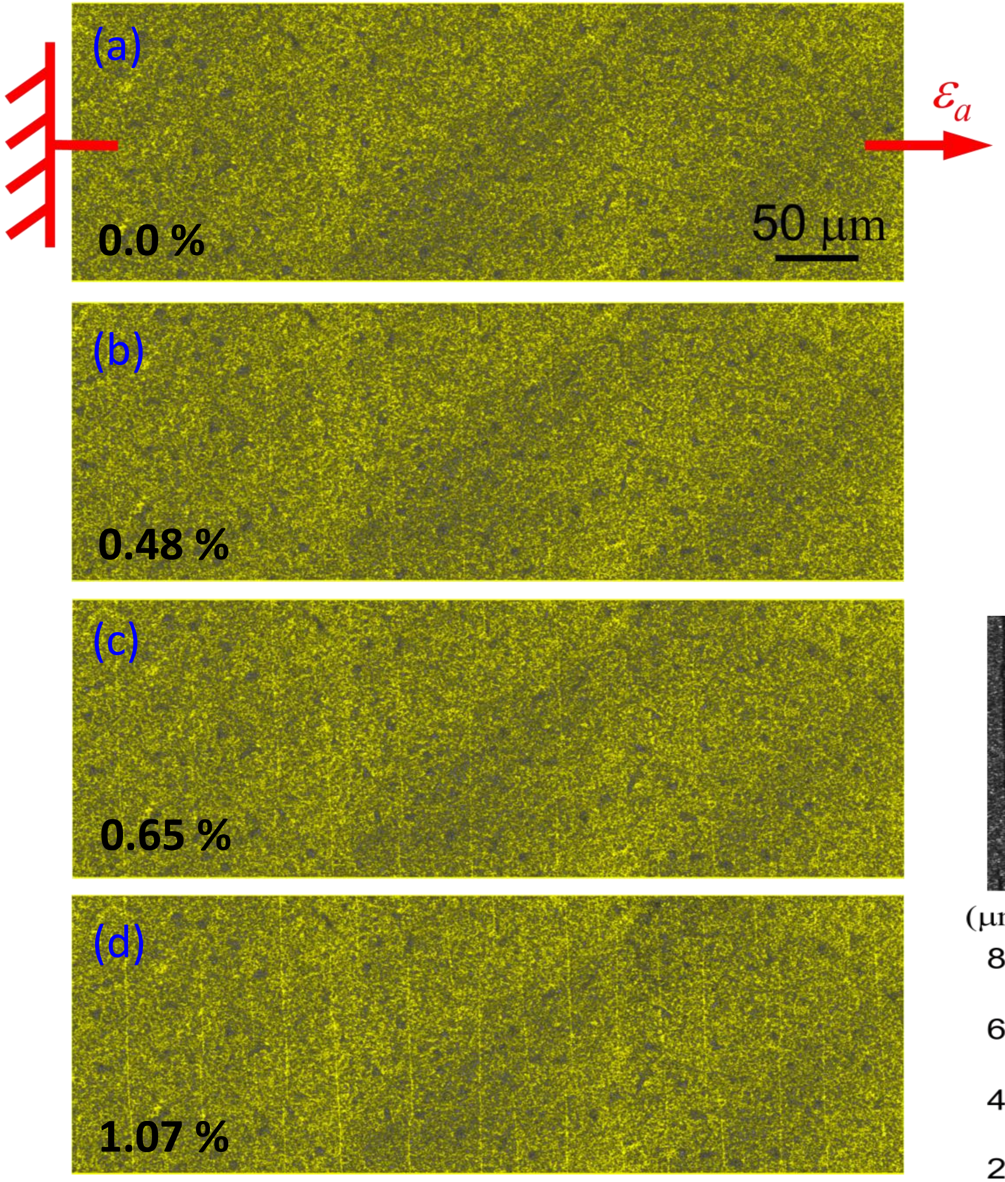
Material	Young's Modulus/Gpa	CTE/ppm
Glass	66	4.5
EVA	0.0677	90
Silicon	112.4	2.49
Backsheet	2.075	88
Al	69	23.4
Silicone Sealant	1	270

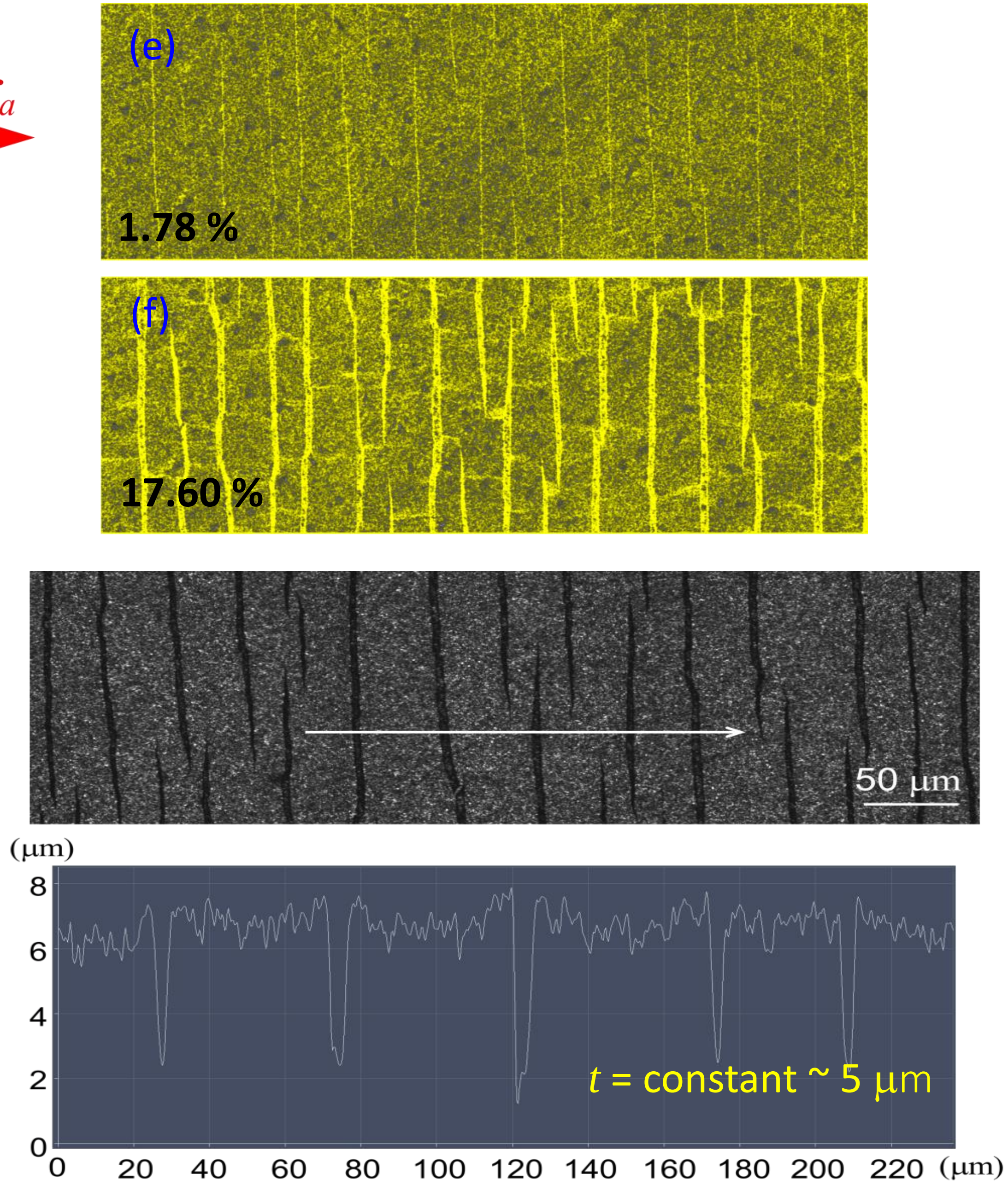
Experiments and FEA for deformation of layers between cells

- ✓ Experimental measurement in cell gap area indicated ≈ 3 % of deformation during temperature cycle from -40 °C to 85 °C
- ✓ Finite Element Simulation indicated ≈ 18 % of deformation in the layer between the cells and backsheet during temperature cycle from -40 °C to 85 °C
  - Backsheets in PV modules experience small strains

**Eitner, Shell-like structure, Chapter 29 (2011)

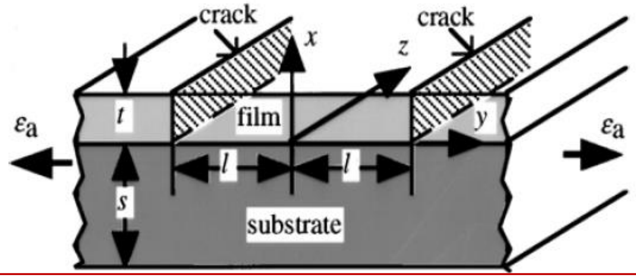
Example of Fragmentation Test – Using SPHERE Exposed PPE Backsheet





**Images are UV humid 11 d conditions

Film Cracking in Film/Substrate Systems – Modeling by Hsueh & Yanaka

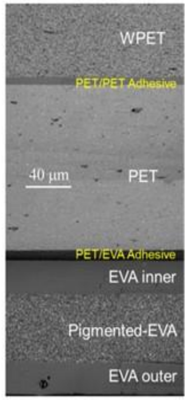


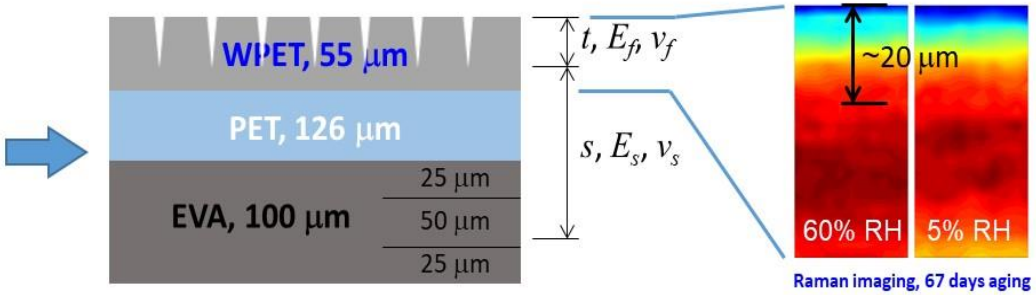
- C.-H. Hsueh and M. Yanaka, J. Mater. Sci., 38 (2003) 1809.

Assumptions:
1. An average stress through the film thickness
2. An *effective* substrate thickness, *s*, which depends on Young's modulus ratio, and film thickness
3. The mismatch strain, *De*, between film and substrate is negligible (original model includes *De*)
4. The change in elastic strain energy in the substrate is negligible compared to that in the film

Film cracking in film/substrate systems – Application to PPE backsheet

- **Assumption:** 7-layer reduced to 3-layer, adhesive layers are seen as interfaces.





Effective substrate modulus and Poisson's ratio (by the rule of mixtures), and crack depth (t) are used for the model!

The cracking behavior can be described by the parameters of ε_a, ε_c, crack spacing ($l = 2/(3r)$, where r is crack density), thicknesses (t, s), and materials elastic properties (E_f, E_s, v_f, v_s).

- The **Film strength** can be expressed as

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

- The **fracture energy**, G, for the film can be expressed as

$$\Gamma = \frac{3}{4\alpha}\left[\frac{E_f \varepsilon_c^2 (1-2v_f v_s + v_s^2)}{(1-v_f^2)}\right] \quad \text{and} \quad \Gamma = \frac{K_{IC}^2}{E_f}$$

where K_{IC} is **mode I fracture toughness**

Aging conditions	Aging time (d)	ε_c (%)	s (µm)	Γ (J/m^2)	K_{IC} (MPa·m$^{1/2}$)	σ_{str} (MPa)
UV dry	11	0.814±0.028	20.25±1.85	2.399±0.139	0.104±0.003	35.5±1.2
	22	0.726±0.009	25.25±2.00	2.197±0.107	0.099±0.002	31.7±0.4
UV humid	11	0.306±0.009	46.10±3.85	0.560±0.026	0.050±0.001	13.3±0.4
	22	0.142±0.008	74.40±4.00	0.158±0.005	0.027±0.0004	6.2±0.3

$\underbrace{\qquad\qquad}_{\text{Aging vs. Cracking}}$

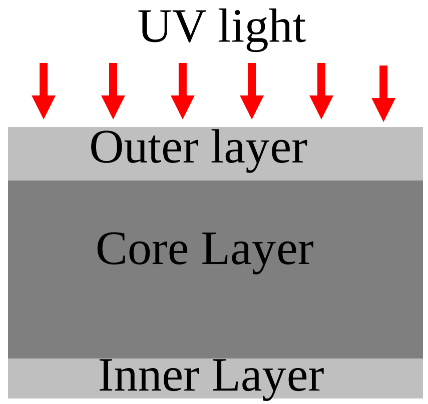
Lin, …, Gu, et al. (2019), Prog Photovolt Res Appl. 27:44–54.

Applying Fragmentation Test to Different Backsheets Aged under A3 Condition

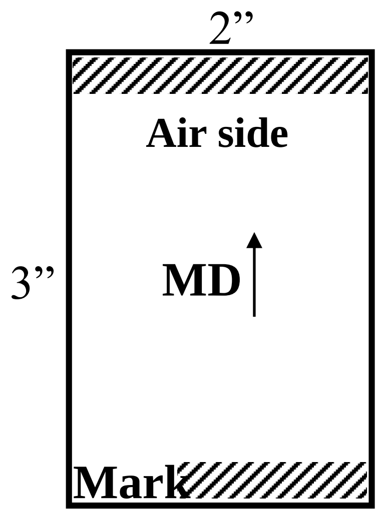
1) Exposure: Simultaneous UV/T/RH *(need to be appropriate)*

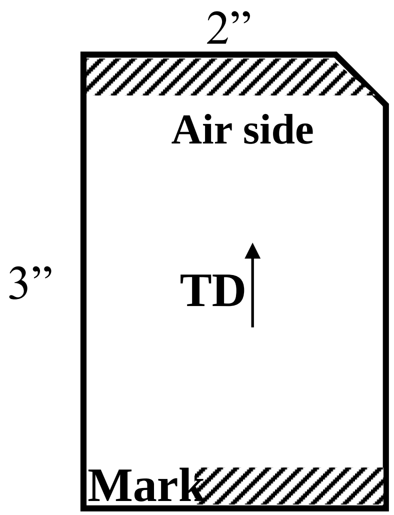
A3 condition in IEC 62788-7-2 (approved 9/2017)

- **UV/65 °C/20 % RH** (Xenon arc lamp, 0.8 W/m^2/nm @ 340 nm, air temperature of 65 ^{o}C, black panel temperature of 90 ^{o}C)
- A3 condition + 120 min light /18 min of spray.
- 250 h, 500 h, 1000 h, 2000 h and 4000 h
- PPE, AAA, PVDF-based, TPT

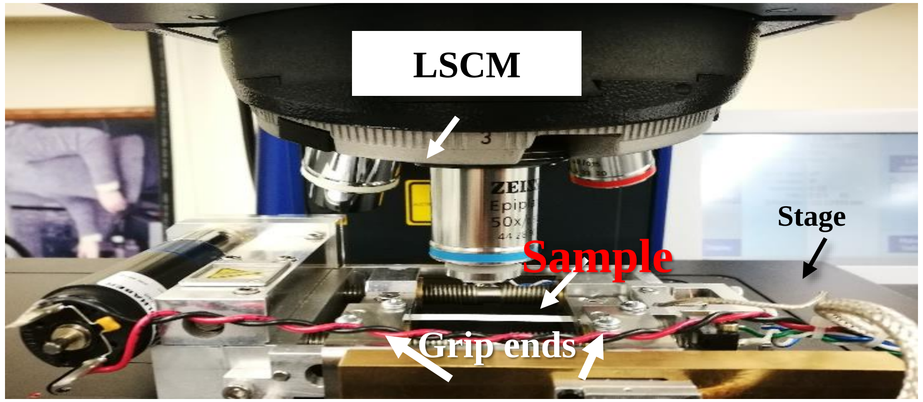


❑ Sample for exposure



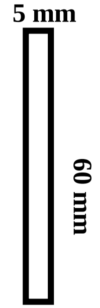


2) Fragmentation test



Miniaturized tensile tester

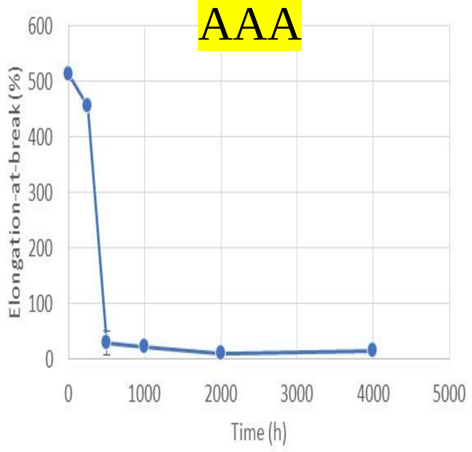
❑ Sample for test

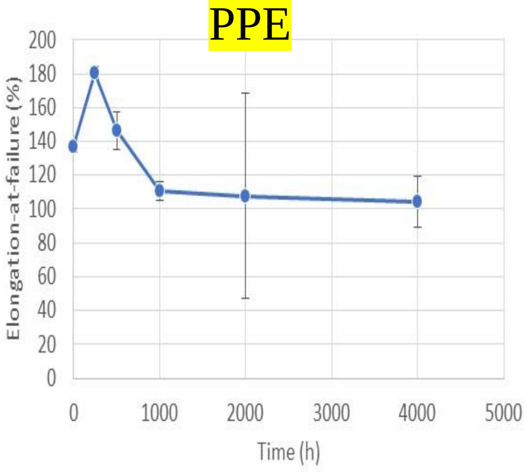


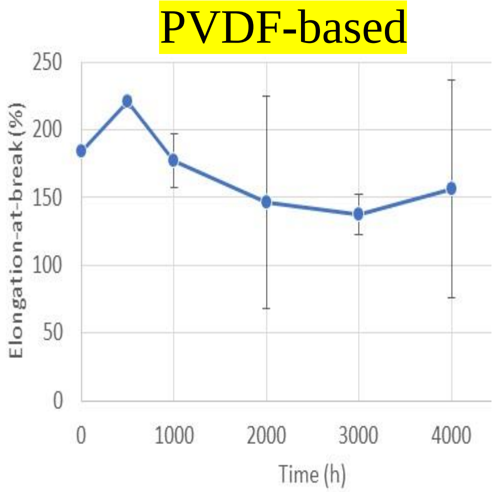
Gauge length: 35 mm

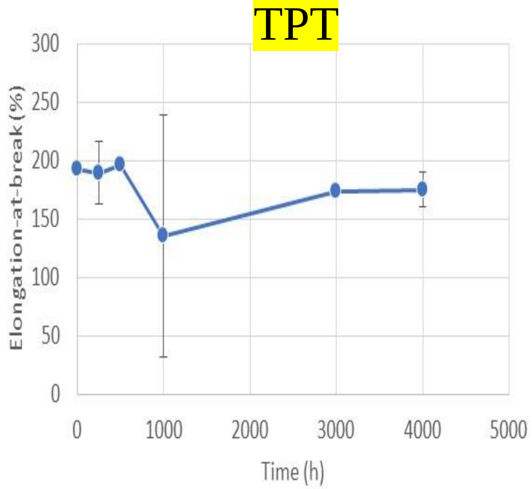
Tensile Test Results of Backsheets as a Function of Exposure Time at A3 Condition

Elongation (%)



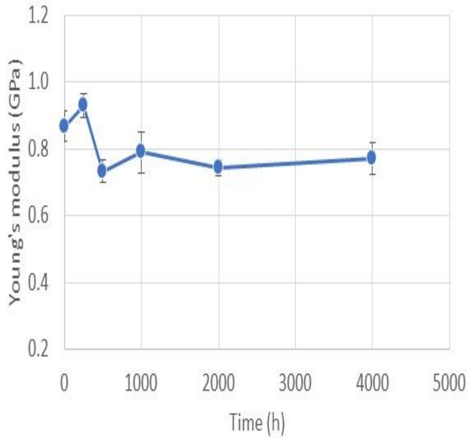


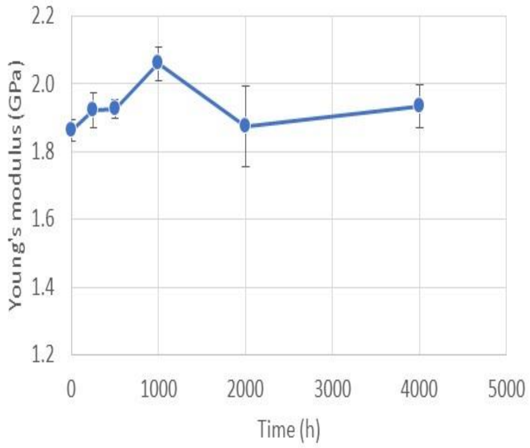


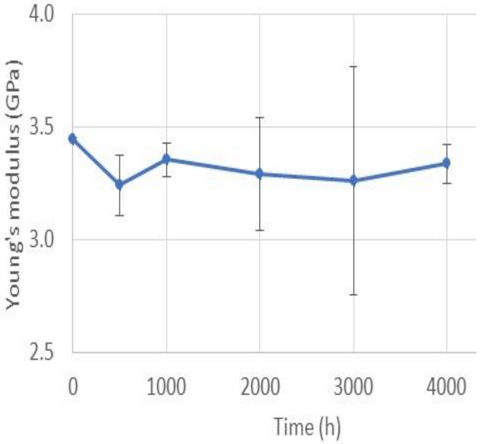


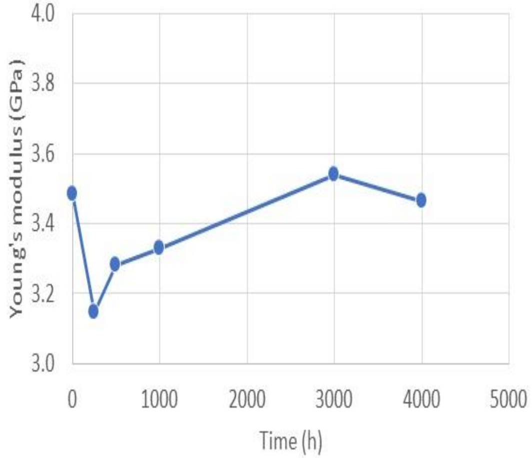
- Significant loss of ductility between 250 h and 50(
- No significant loss of ductility
- Slight loss of ductility

Young's Modules (GPa)







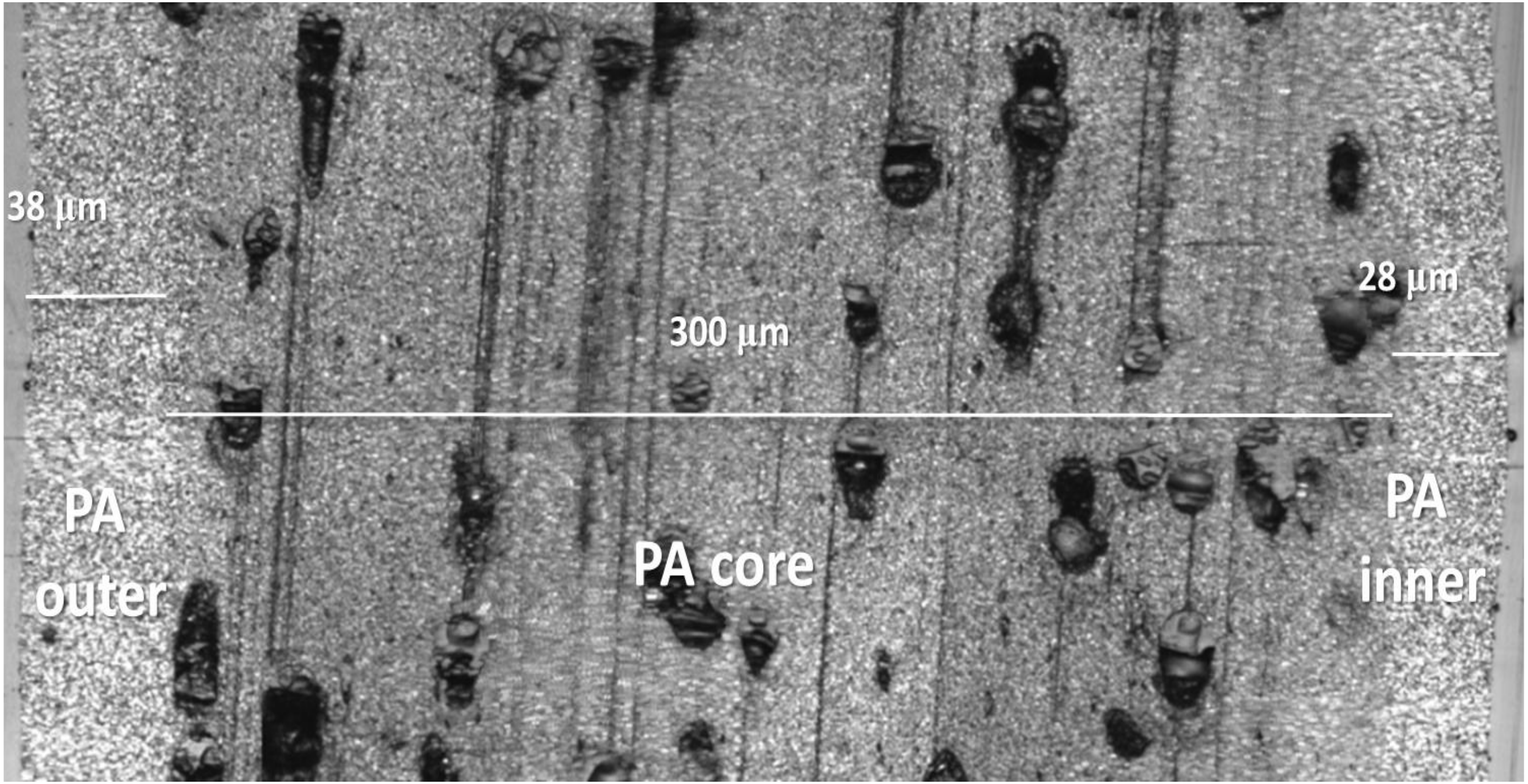


- Marginally lower moduli after 250 h
- Marginal changes in moduli with initial stiffening
- No significant changes in stiffness

➢ Except for AAA, no other materials showed substantial changes in elongation during 4000-h exposure based on tensile tests of backsheet films, probably due to the core layer effect.

1. Backsheet Characterization- AAA

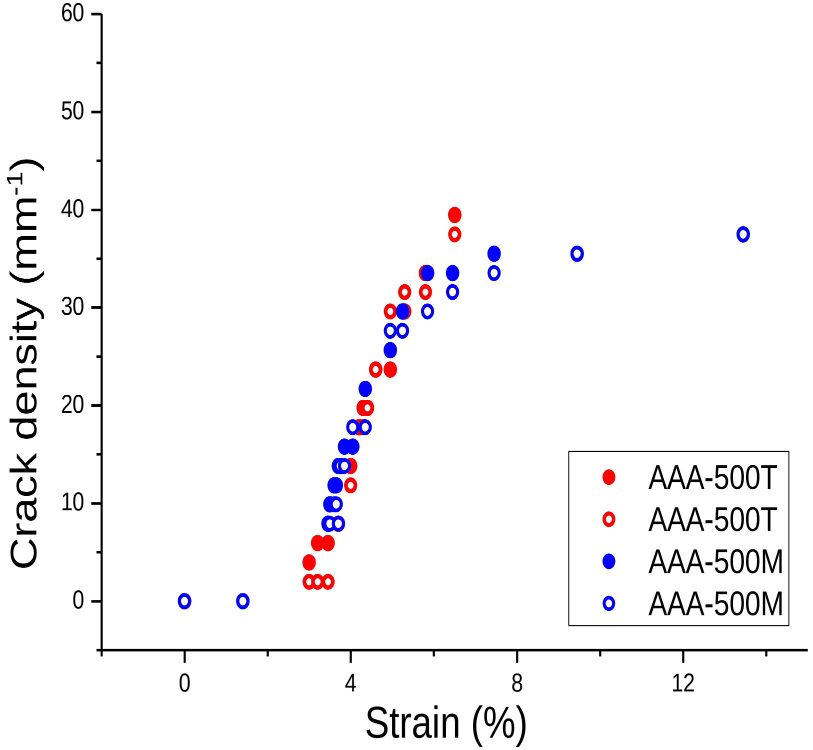
(Laser Scanning Confocal Microscopy, LSCM)

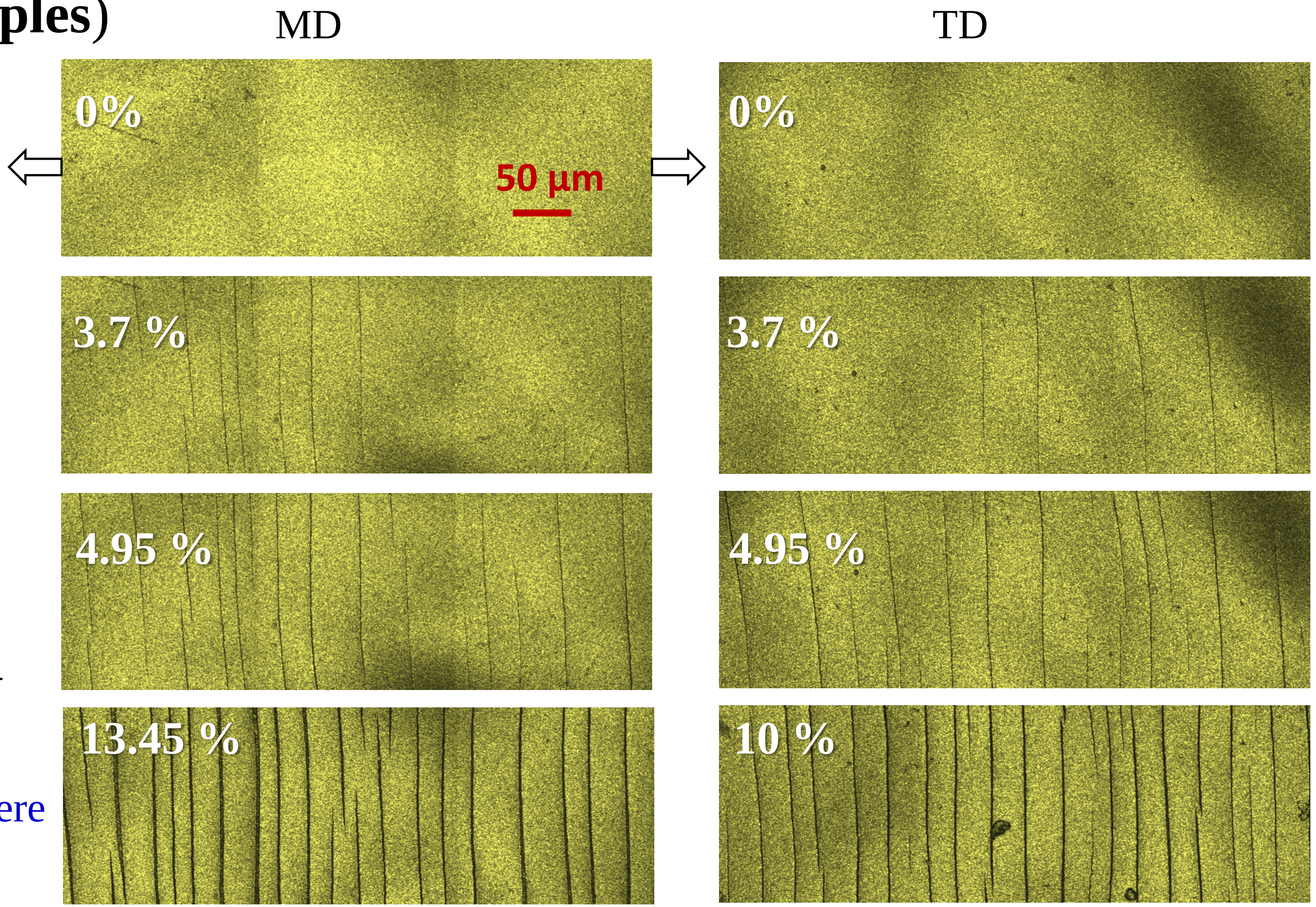


Fragmentation Test Results (LSCM)

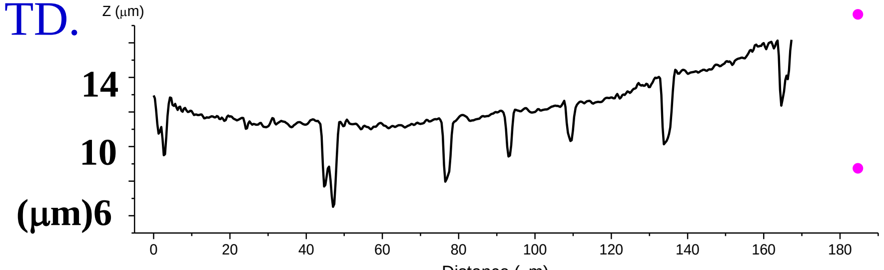
AAA (500 h, MD and TD samples)

No cracks for 250 h





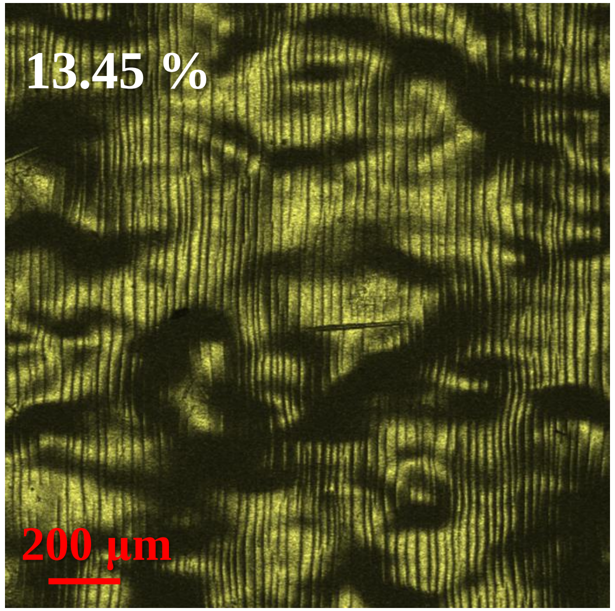
- Under tension, periodic surface cracks were observed perpendicularly to the stress direction.
- No obvious difference between MD and TD.
- Early detection (~500 h) of cracking propensity.

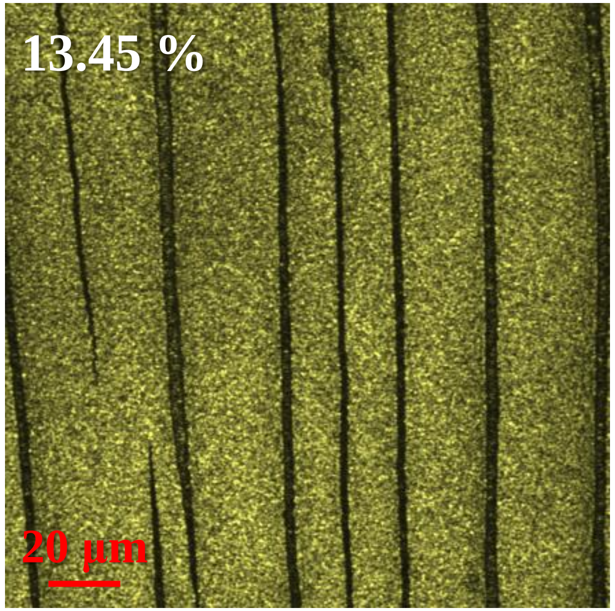


- *Surface cracking vs. across film cracking (initiation, based on cracking propagation)*
- *Importance of surface cracking –UV vs. DH*

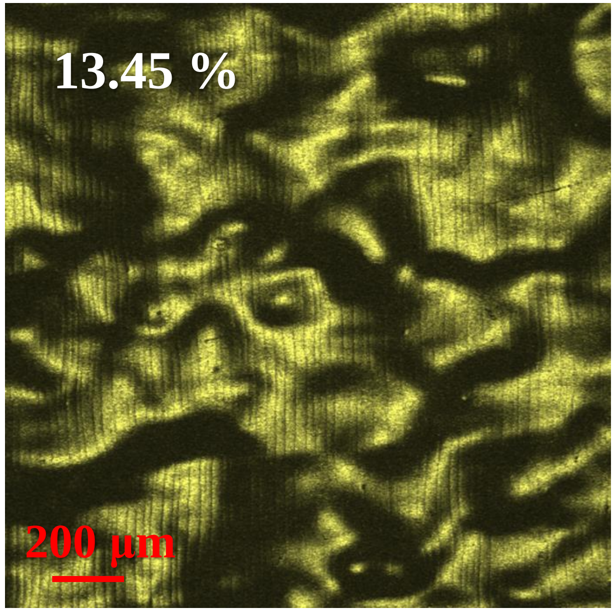
➢ Crack Recovery Test after Release of Load- AAA (500 h, MD)

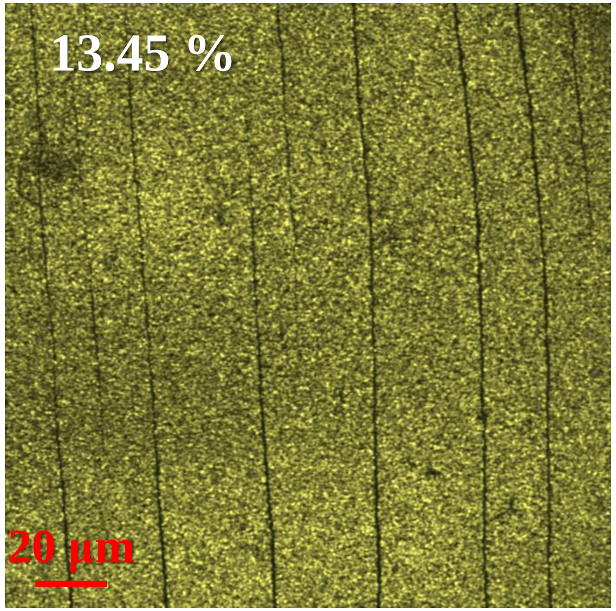
Under tension (LSCM)





Released from tension (LSCM, overnight)

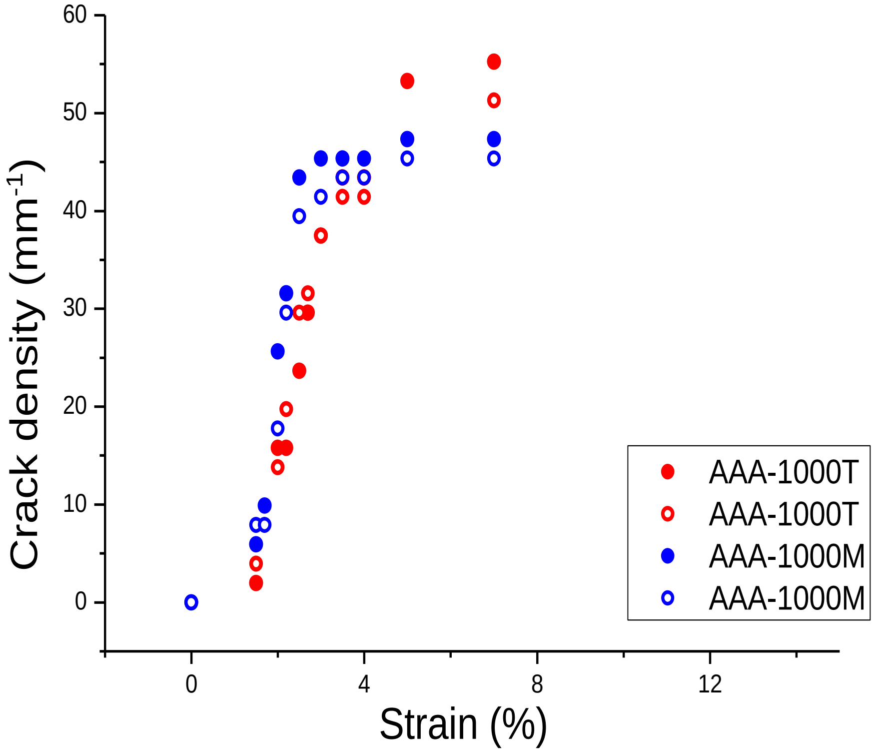


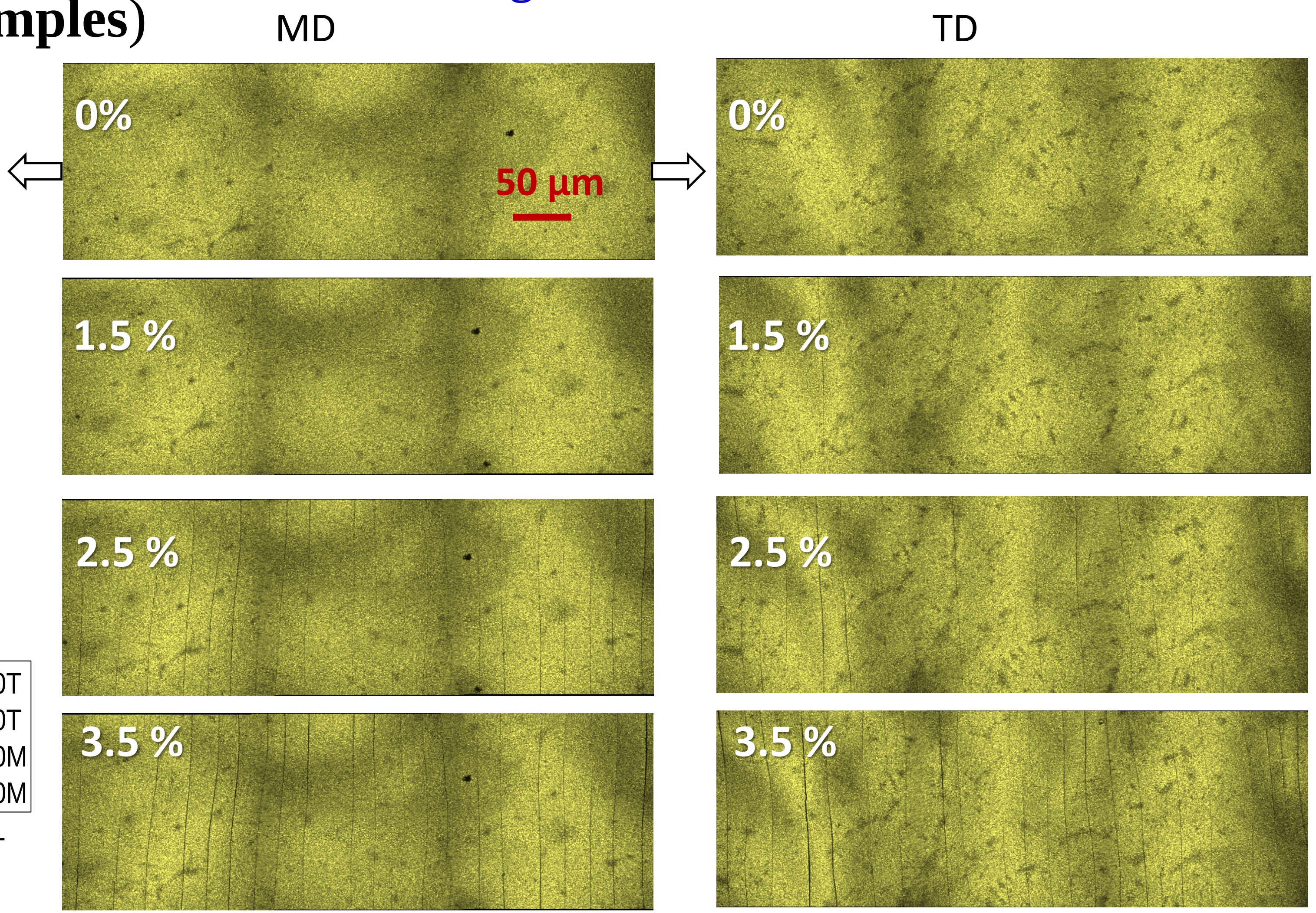


- Cracks are still obvious after release of tension

Fragmentation Test Results

AAA (1000 h, MD and TD Samples)

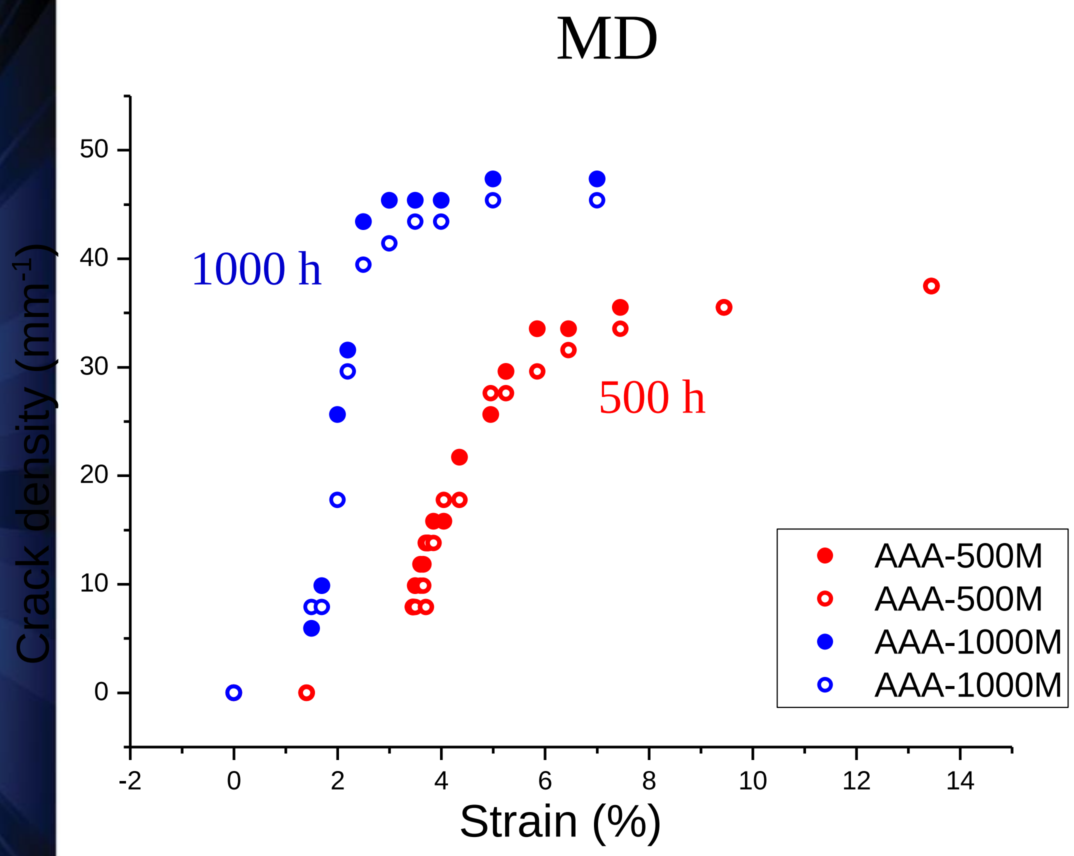


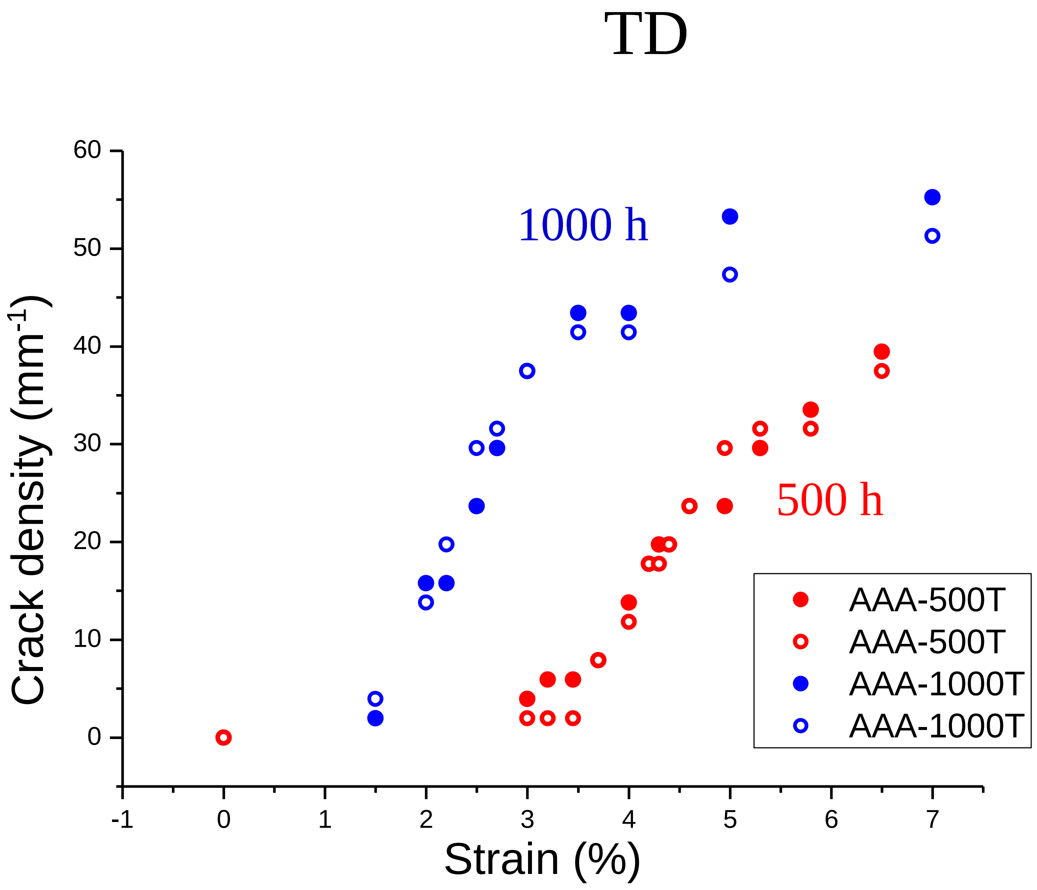


- Similarly, periodic surface cracks were observed perpendicularly to the tensile direction. (Material response to the uniaxial stretch)

AAA

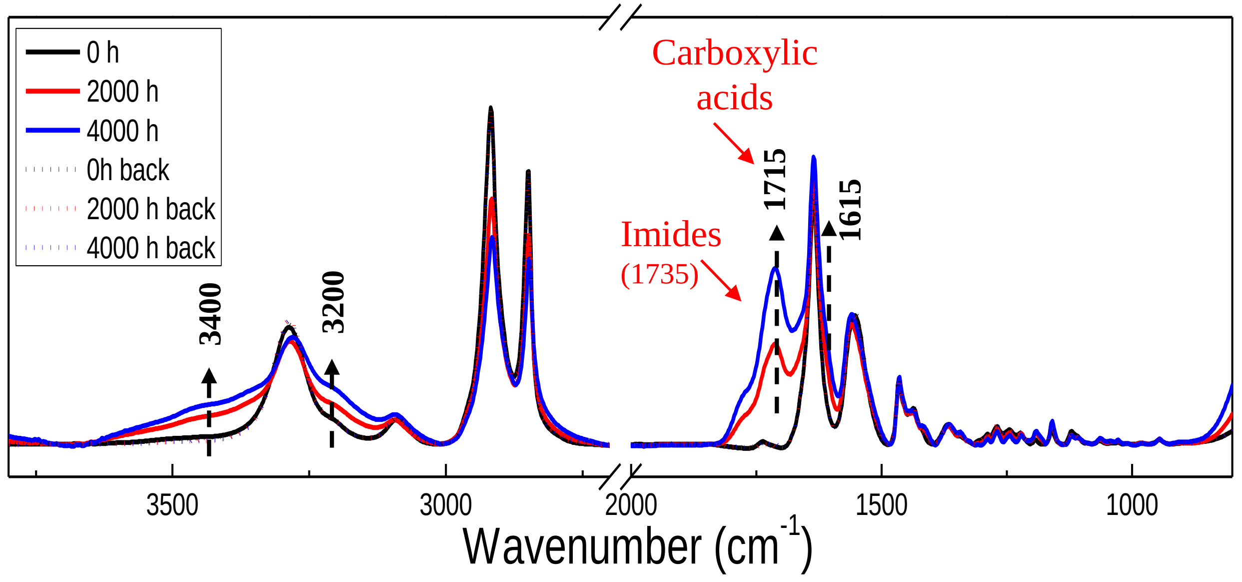
Fragmentation Test Results (Effect of Aging Time)



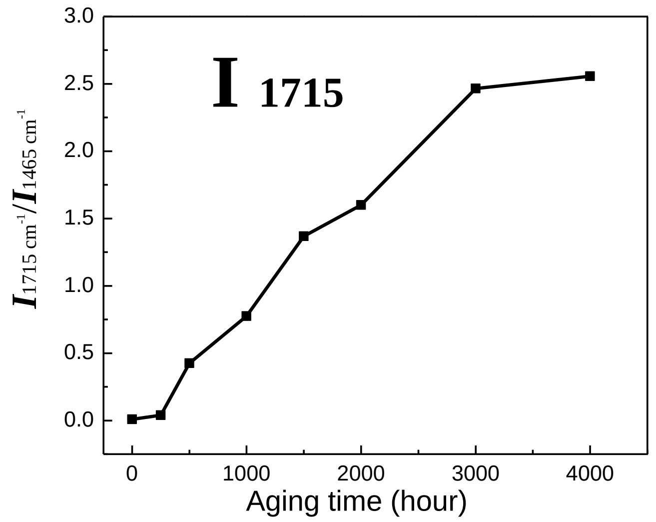


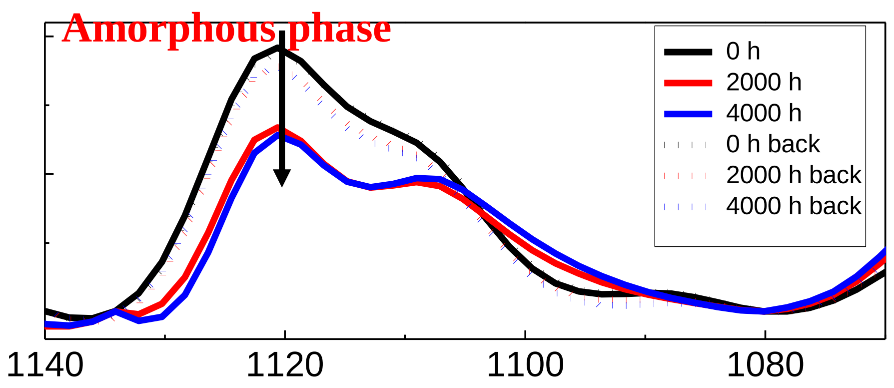
- Lower critical strain for a longer exposed AAA sample for both MD and TD directions.

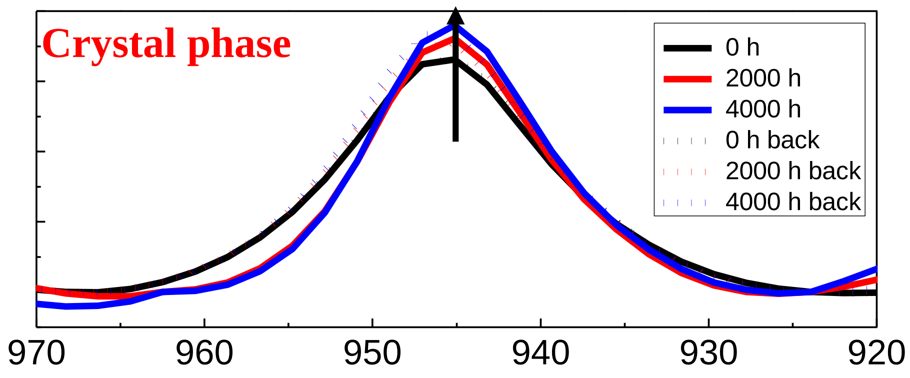
ATR-FTIR Spectra of AAA Backsheets after A3 Exposure (Surface)



Carboxylic Acid Formation



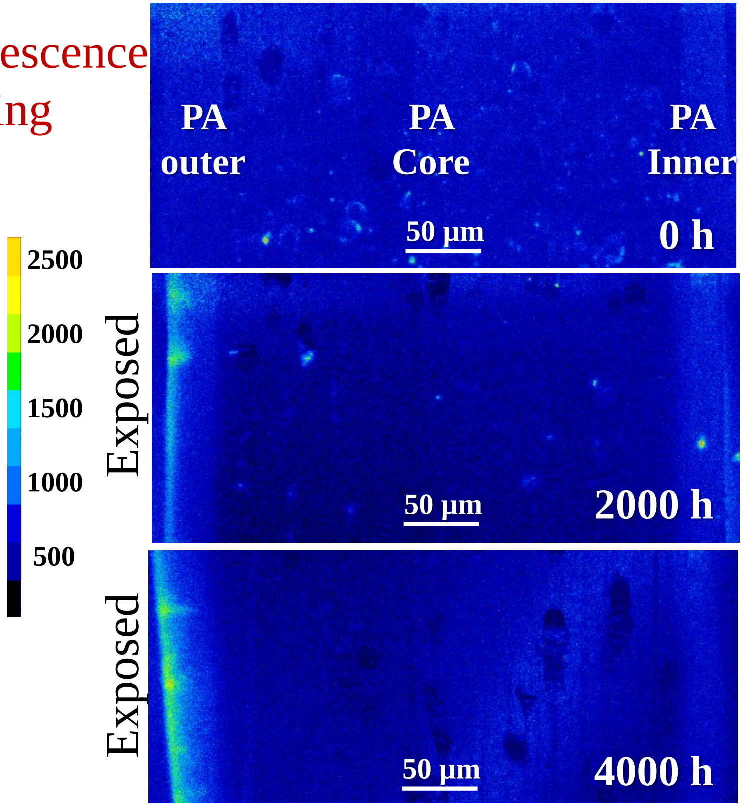


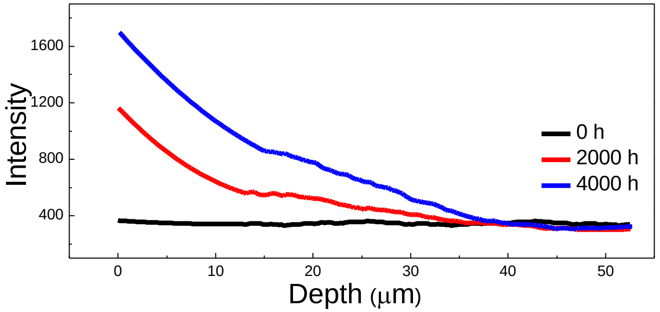


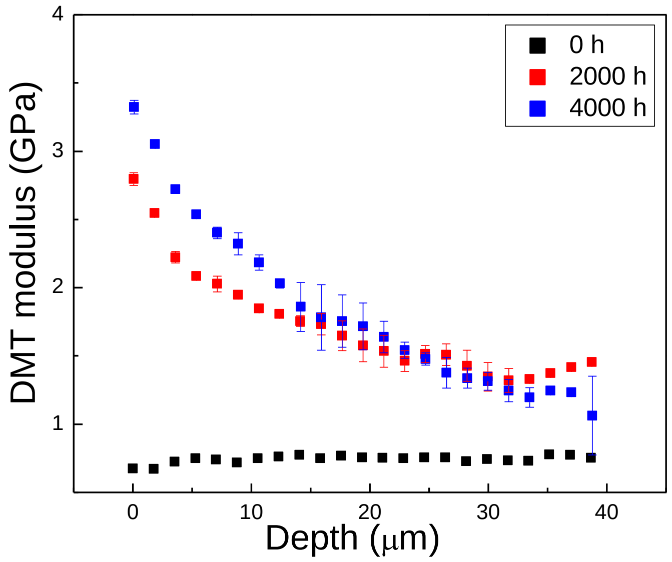
- ***Significant chemical degradation was observed for UV exposed surfaces.***
- **Acid formation increases with the longer exposure time on the surface of the UV exposed AAA.**
- **Decrease in the the amorphous phase, while enhancement in the crystal phase.**

Depth Profiling of Chemical and Mechanical Degradation of Aged AAA (Cross-section)

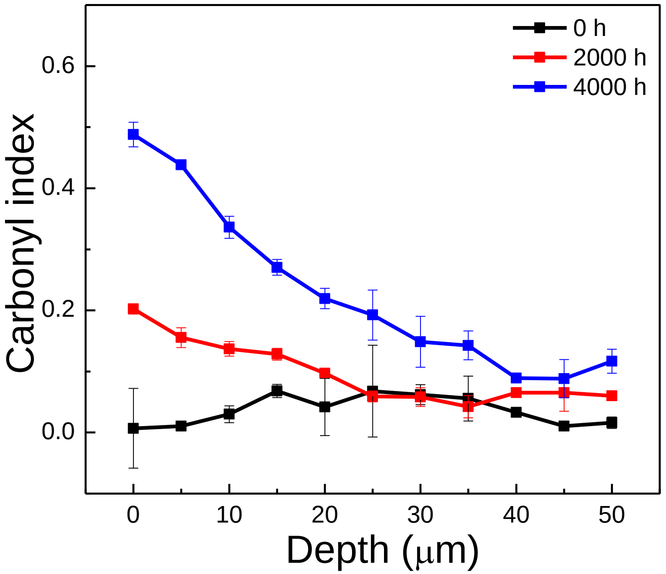
Fluorescence imaging







AFM-QNM



Micro-FTIR

- **Degradation is mainly confined in the top~ 30 μm layer from the exposed surface. then gradually decreases into the bulk. (using H-Y model: brittle surface on the substrate)**

Fracture Energy of Surface Cracking after UV Exposure by HY's model

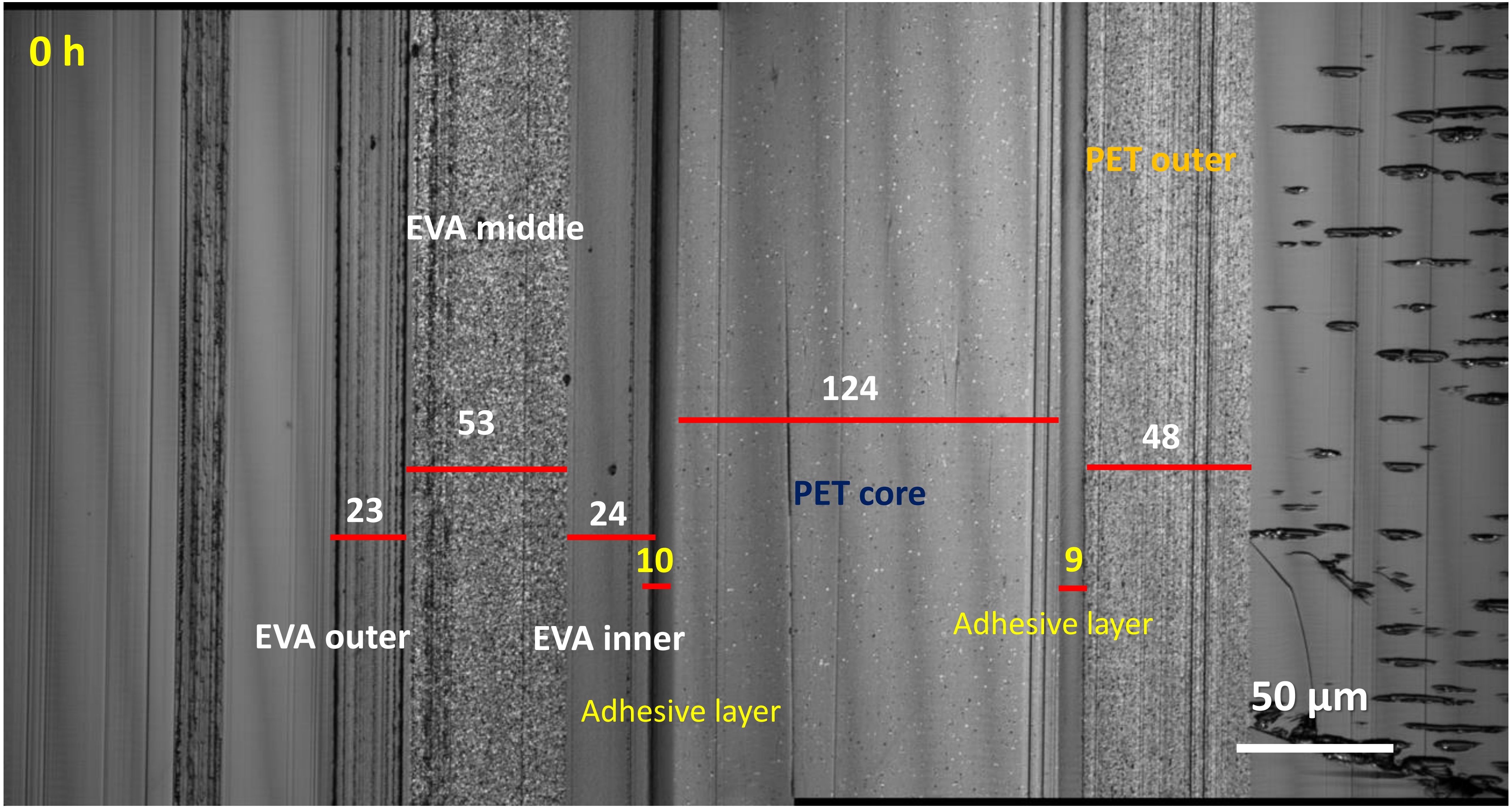
Hsueh and Yanaka, J. Mater. Sci, 2003.

Aging condition	Aging time (h)	Critical strain, ε_c (%)	Crack depth (μm)	Effective substrate thickness, *s* (μm)	Fracture energy, Γ (J/m²)
65°C/20%RH Xenon arc	2000	1.65±0.033	2.0±0.3	55.3±1.4	9.25±0.23
	4000	0.95±0.046	5.0±0.8	161.4±6.6	8.05±0.60

- **The calculated fracture energy decreases with increasing exposure time, indicating a higher crack propensity for PA-based backsheet with a longer UV exposure time.**

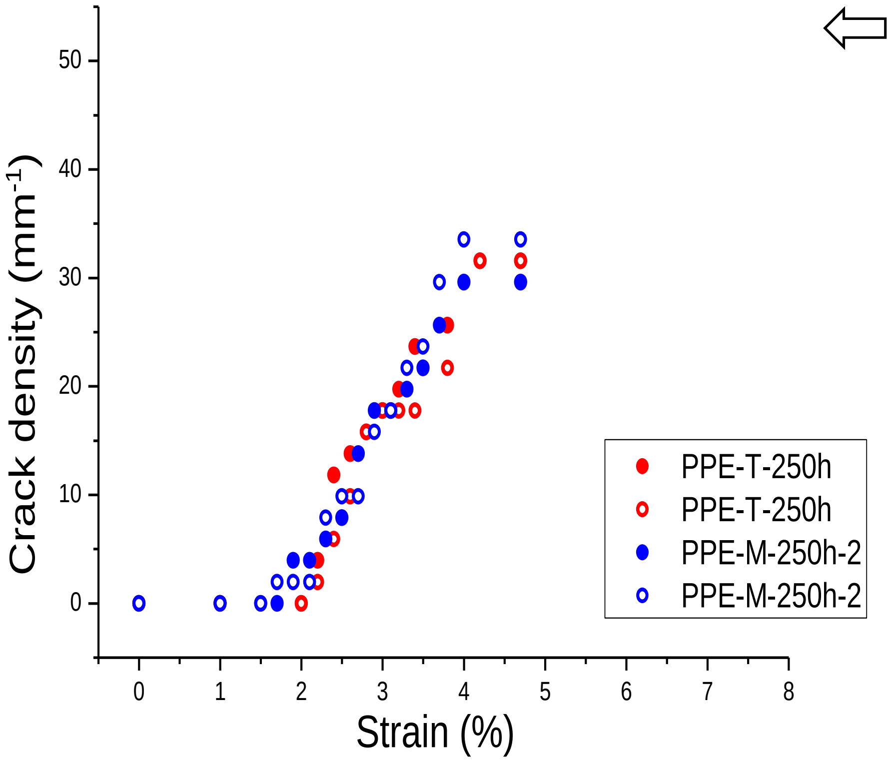
Lyu, Kim, Fairbrother, Gu (2019), IEEE J. Photovoltaics, DOI:10.1109/jphotov.2018.2863789

2. Backsheet Characterization (LSCM): PPE

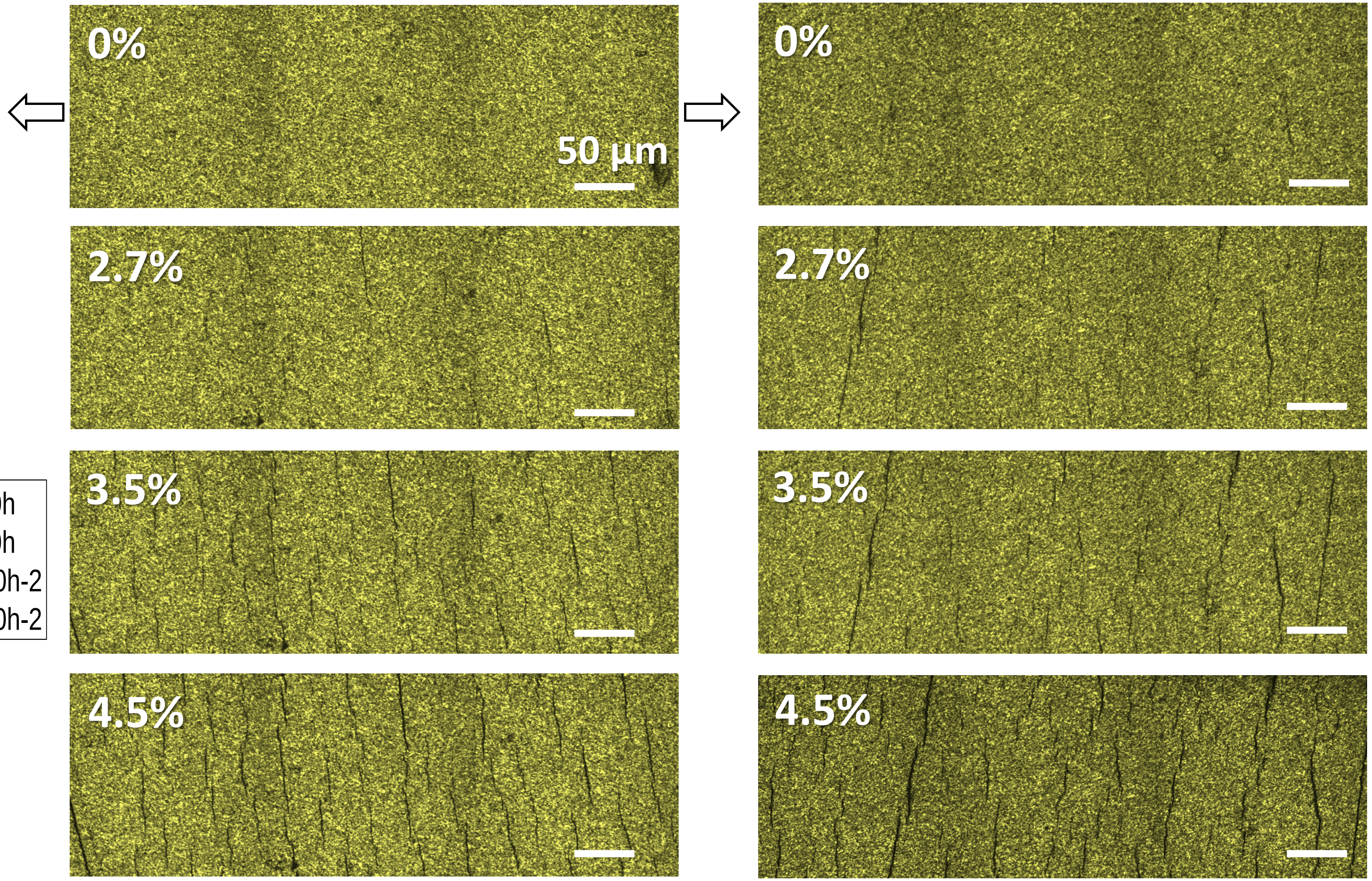


PPE (250 h)

Fragmentation Test Results (MD vs. TD)

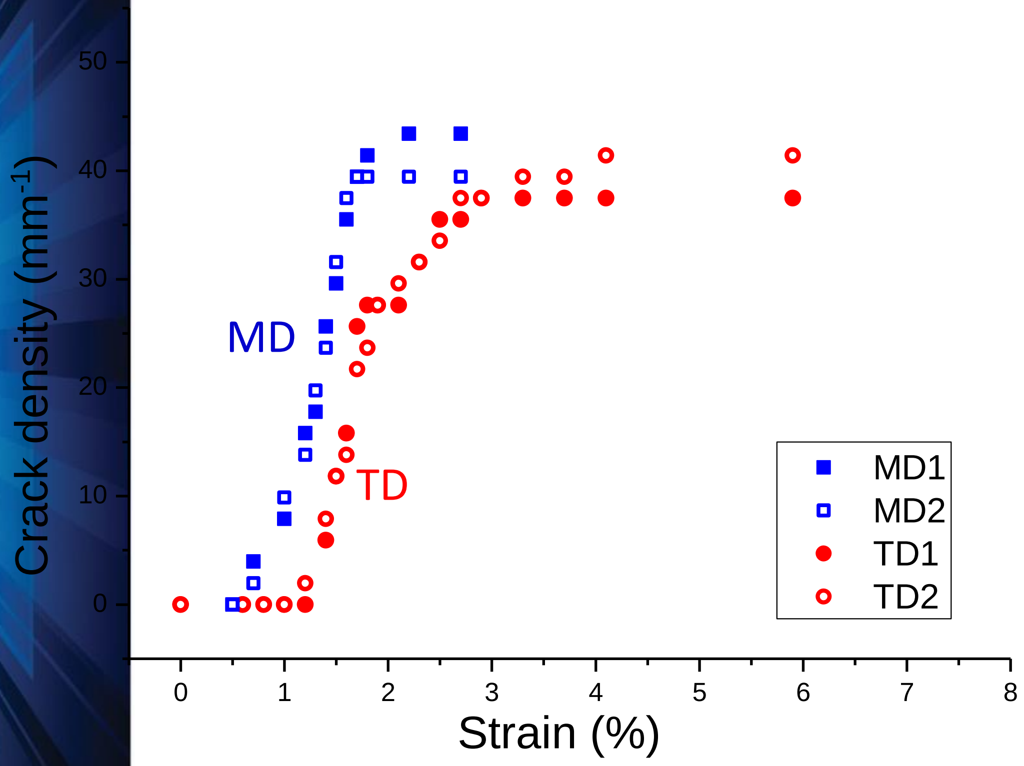


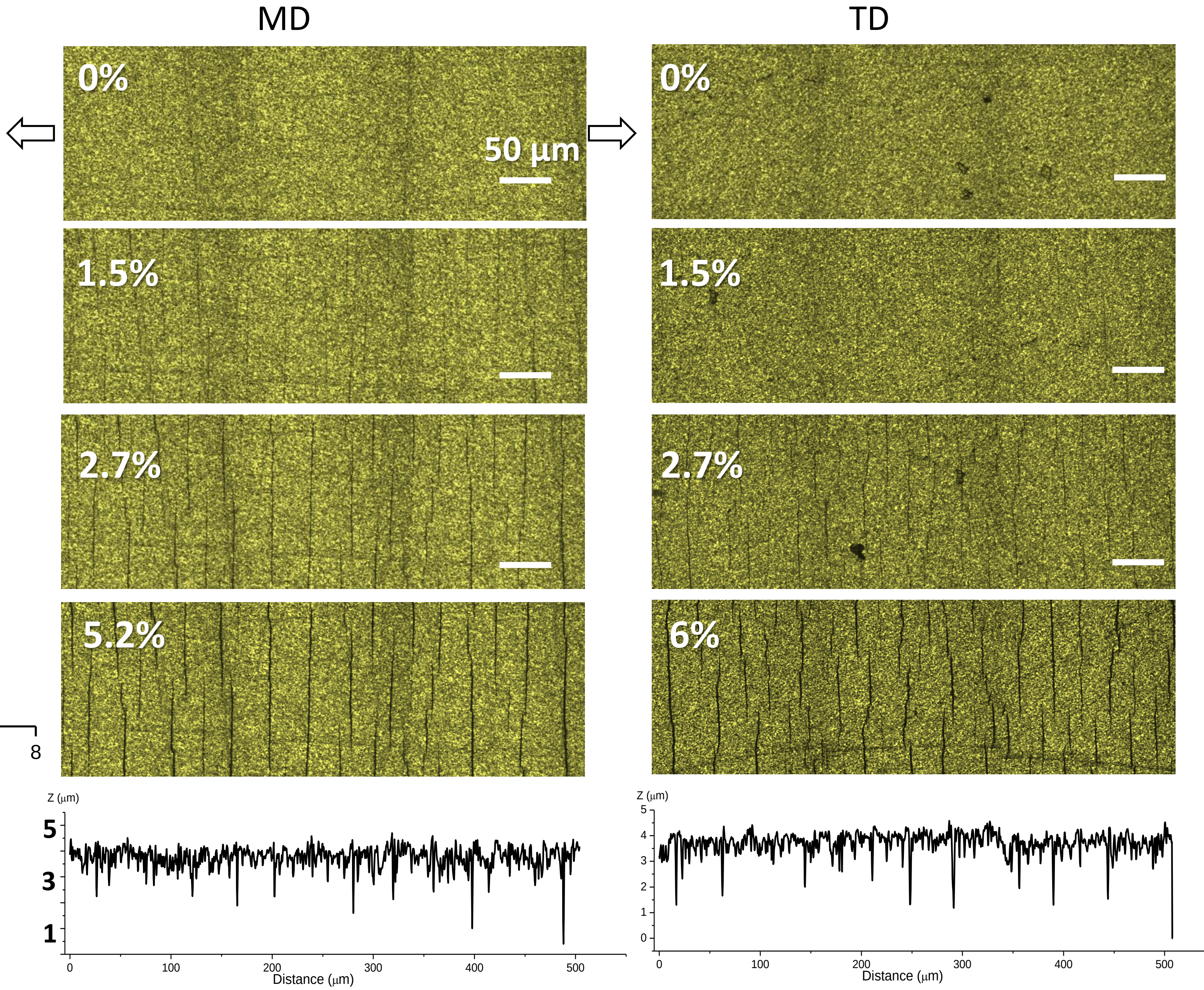
MD TD



PPE (500 h)

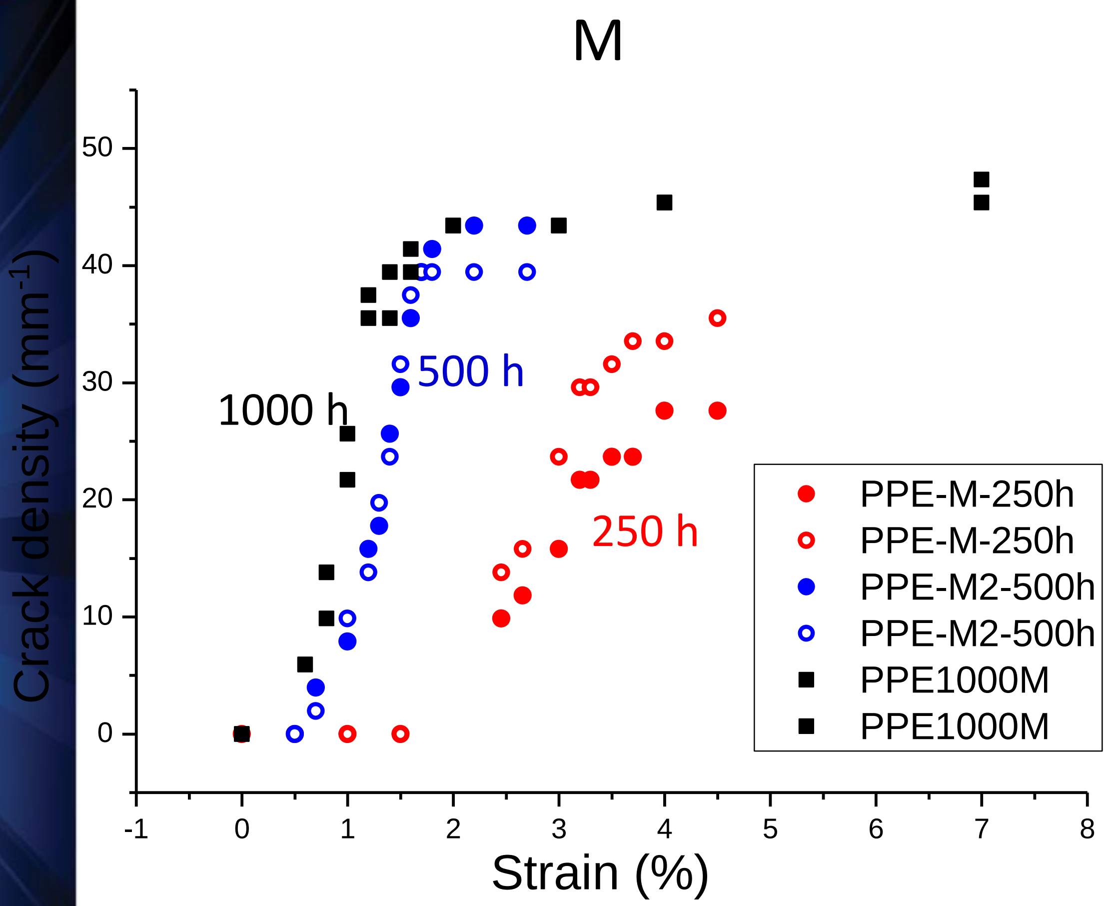
Fragmentation Test Results (MD vs. TD)

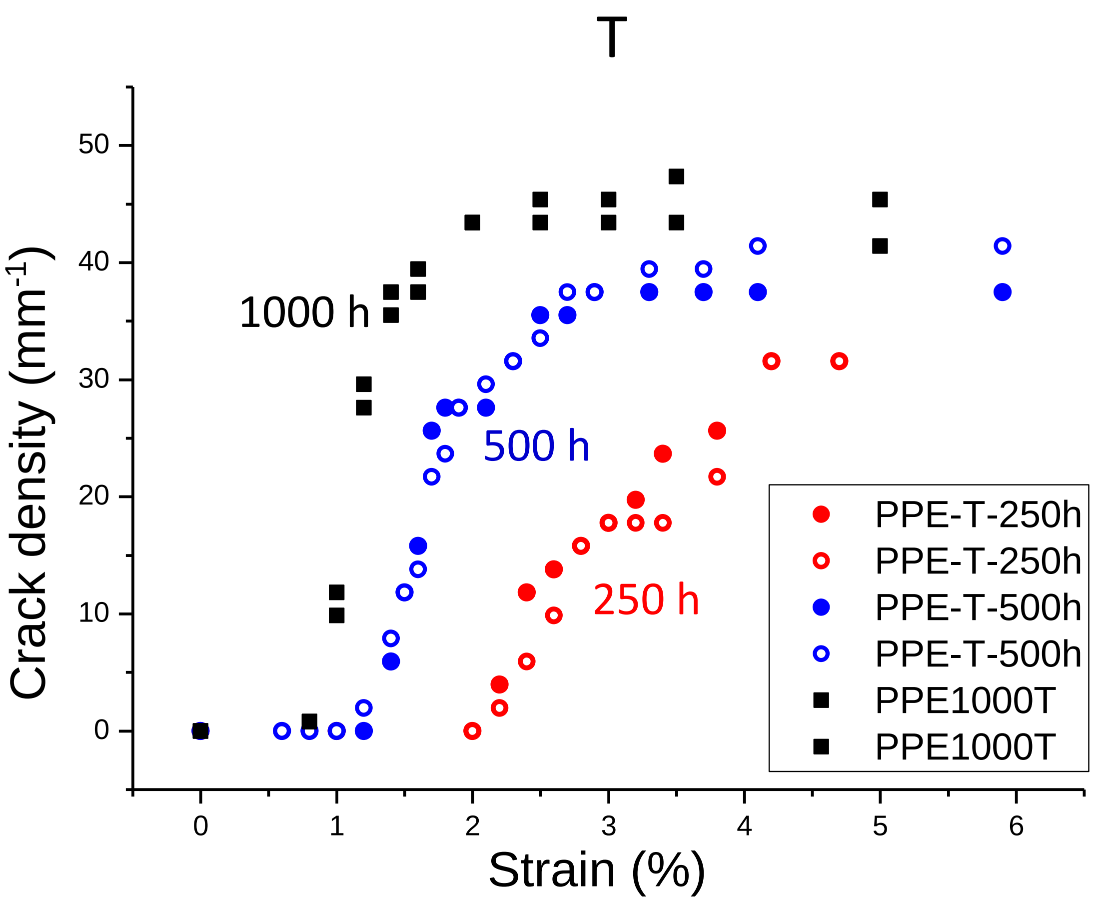




PPE

Fragmentation Test Results (Effect of Exposure Time)



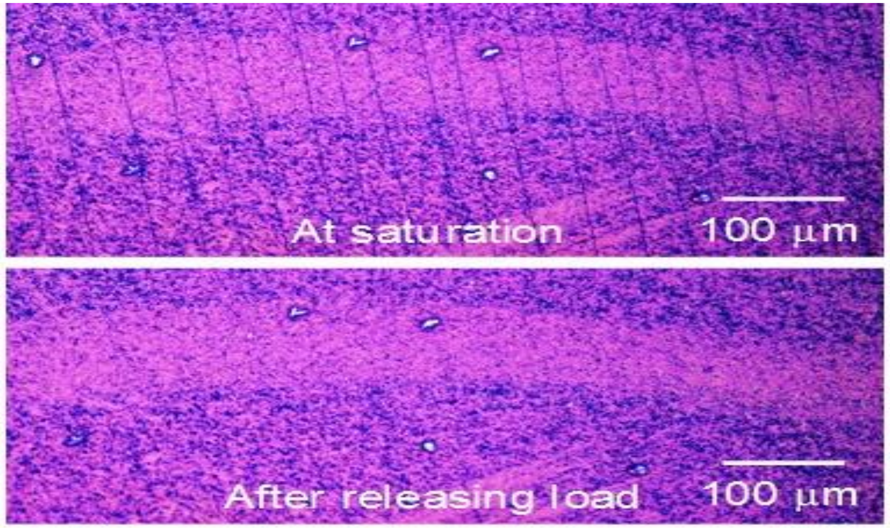


- Cracking occurs at lower critical strain with increasing exposure time for both MD and TD.

Crack Open/Closure after Releasing Load (PPE vs. AAA)

PPE after Releasing Load

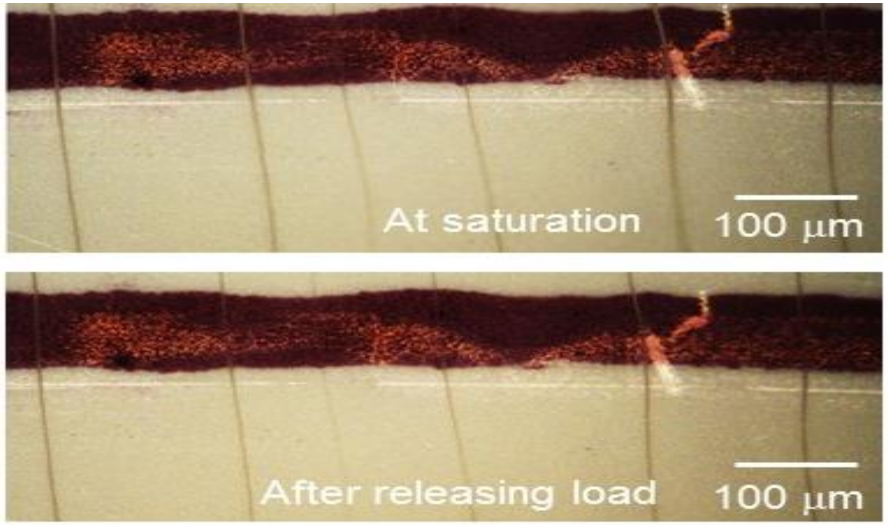
strain ~3%



- Invisible crack after releasing load

AAA after Releasing Load

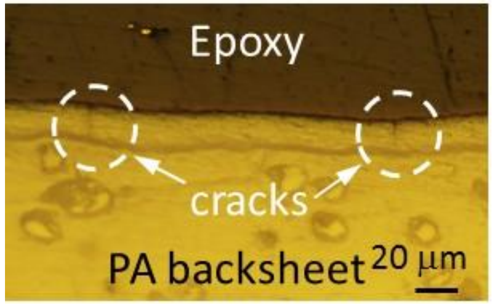
strain ~3%



- Visible crack after releasing load

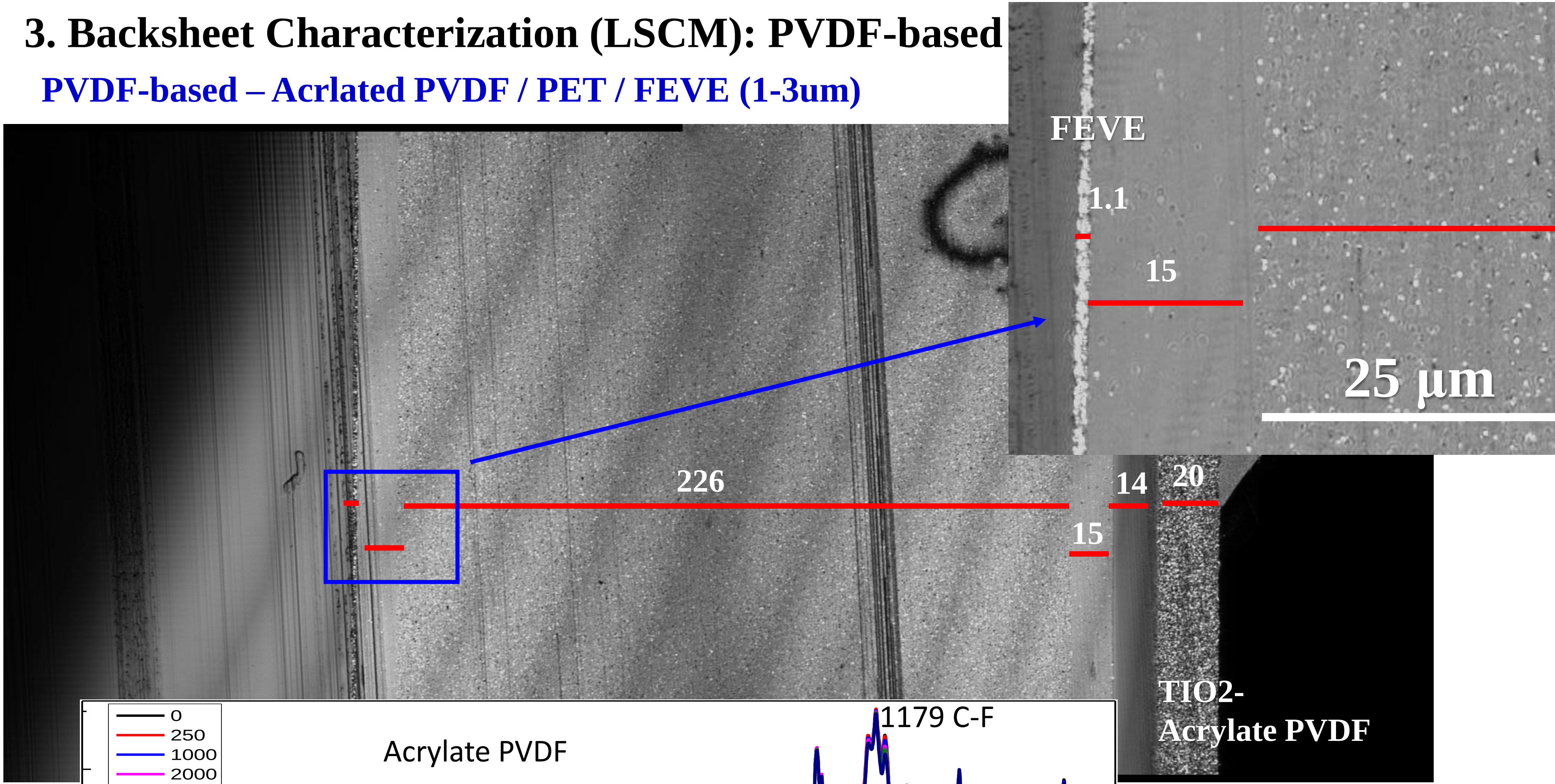
- NIKON ECLIPSE LV100N microscope for imaging

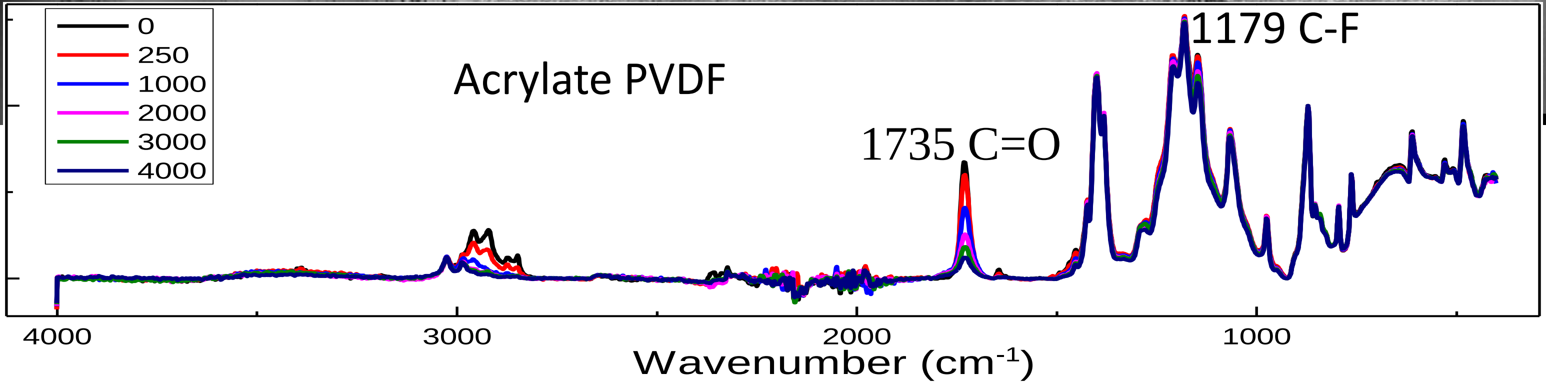
Cross-section of AAA based backsheet shows the fragmentation cracks can go through the outer layer of AAA



3. Backsheet Characterization (LSCM): PVDF-based

PVDF-based – Acrlated PVDF / PET / FEVE (1-3um)

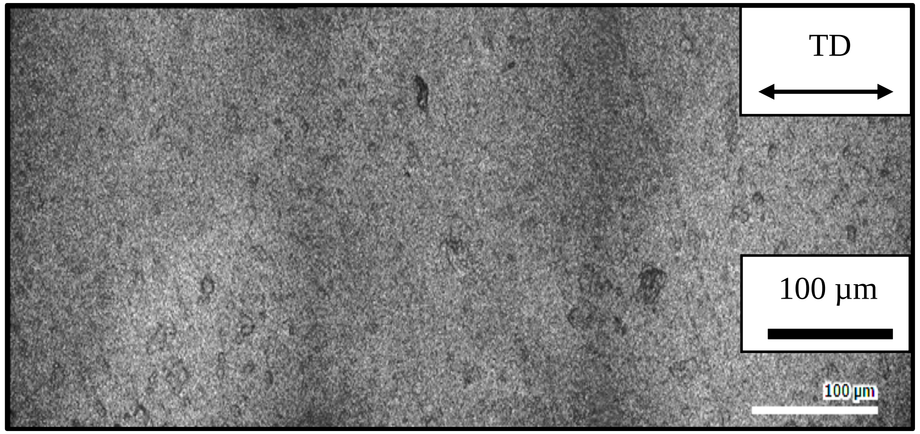




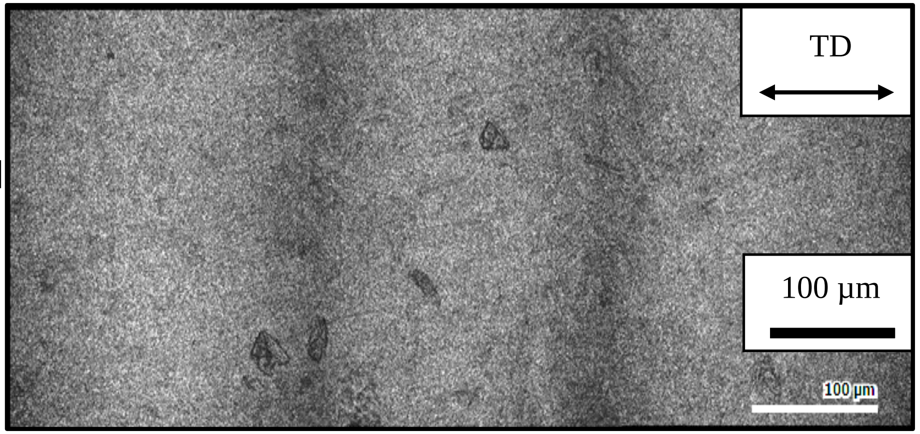
LSCM images of PVDF (3000h & 4000h with Water Spray –TD stretching)

(Pulling rate: 0.33 mm/sec)

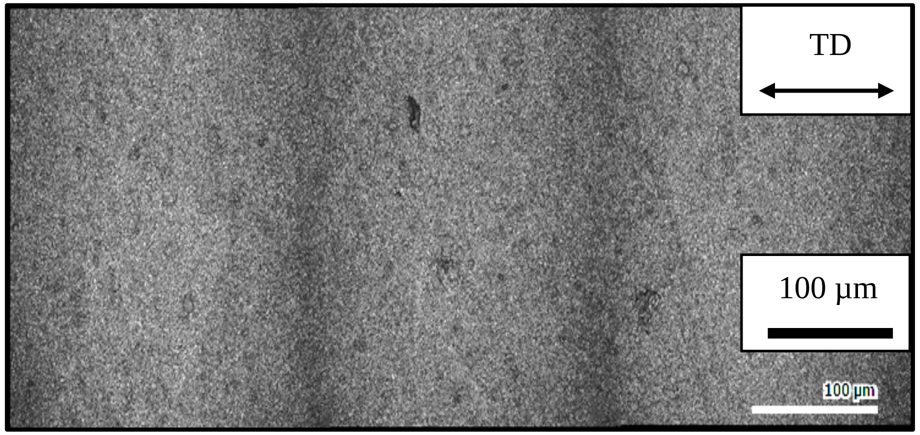
- PVDF 3000s (strain: 0%)



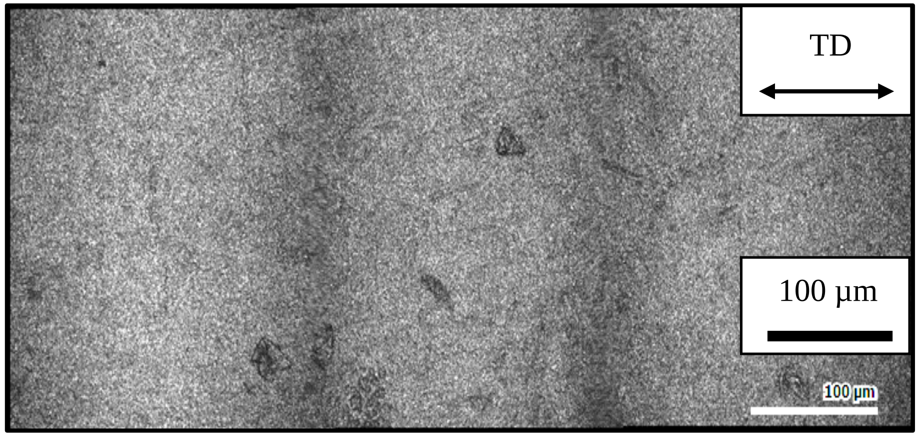
- PVDF 4000s (strain: 0%)



- PVDF 3000s (strain: 5%)



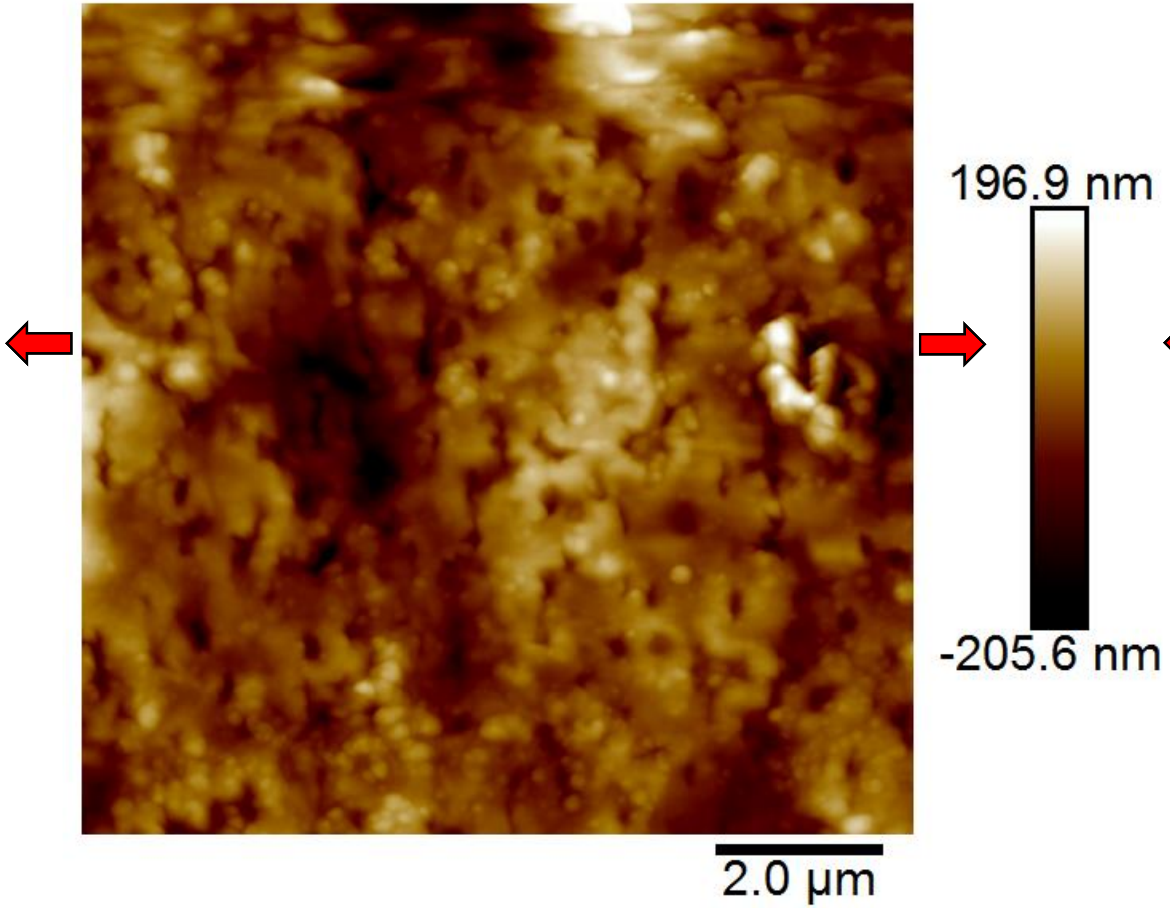
- PVDF 4000s (strain: 5%)



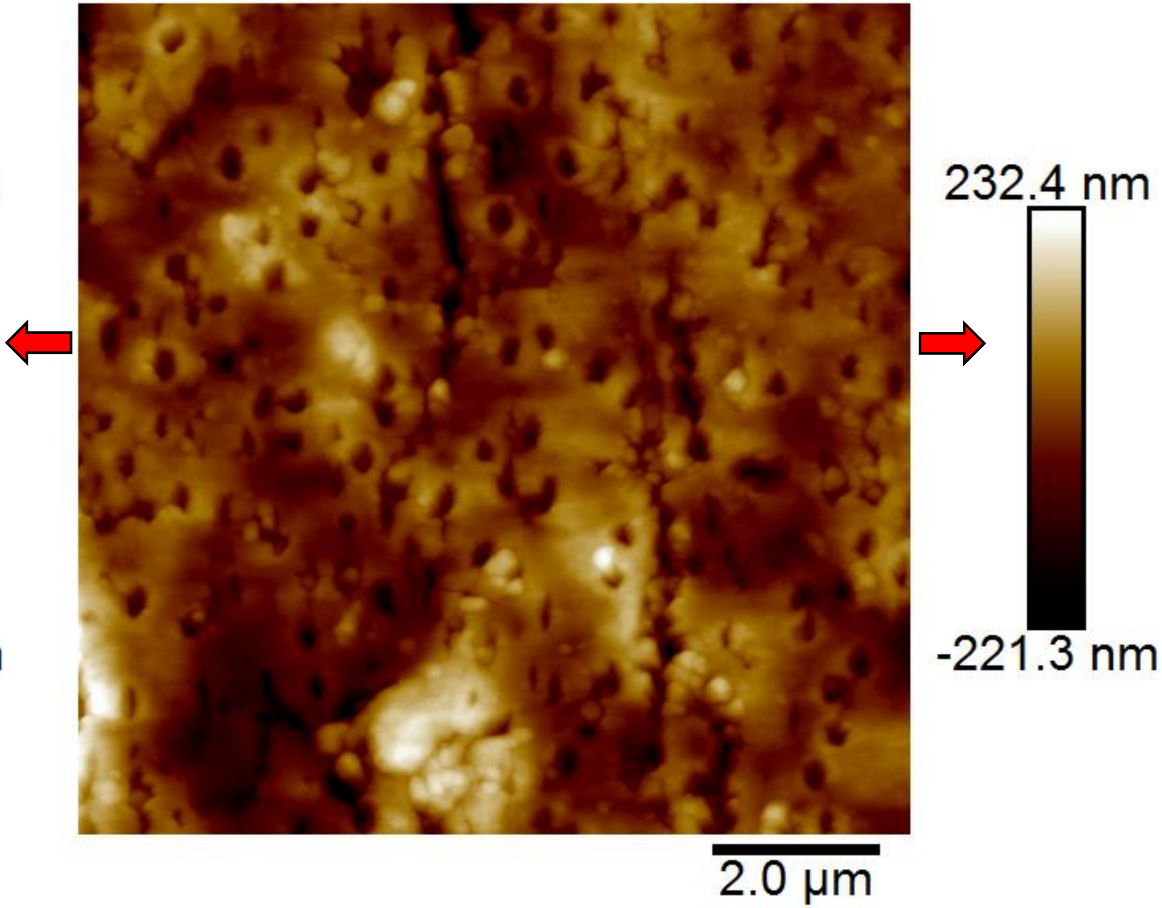
➢ Neither 3000 h nor 4000 h samples with water spray showed cracks under 50x lens.

AFM Height Images on TD, 5% Strain

- Depth profile of 3000s aged PVDF (strain:5%)



- Depth profile of 4000s aged PVDF (strain:5%)



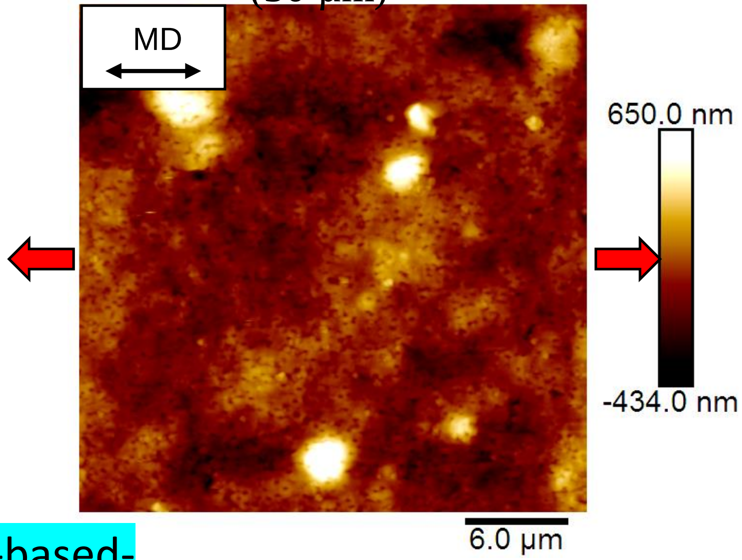
Deformed holes and micro-cracks were observed after sample was first stretched in TD , then relaxed.

AFM Topographic Images after Strain MD vs. TD

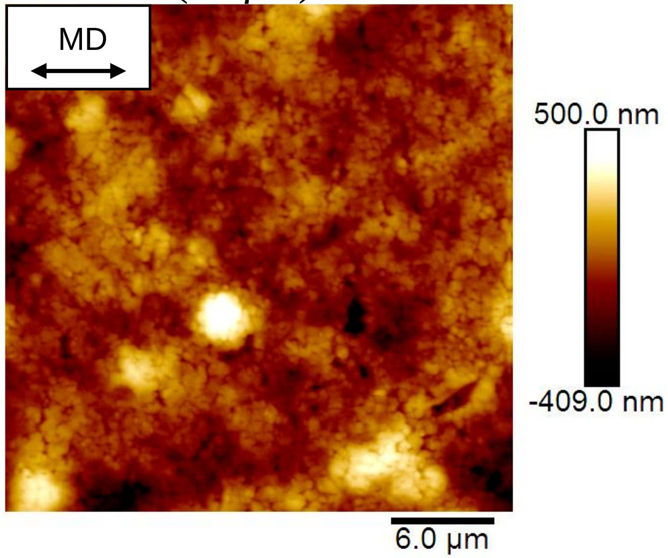
PVDF-based-4000s-MD

MD

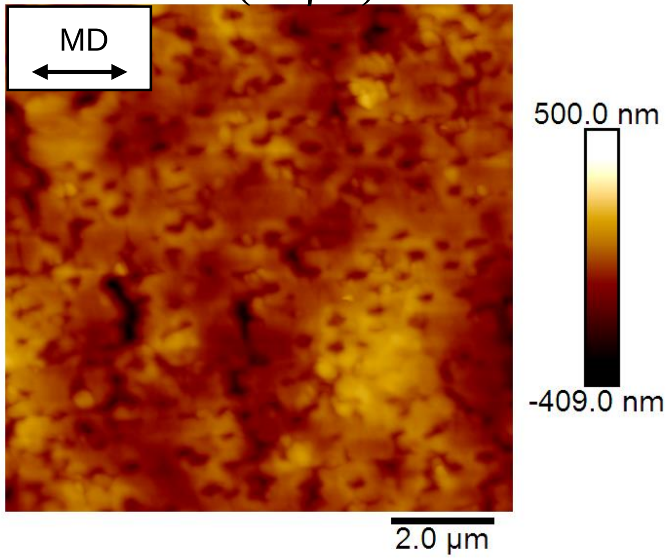
Before Strain (30 μm)



After 25% strain, Relax for 5 days (30 μm)



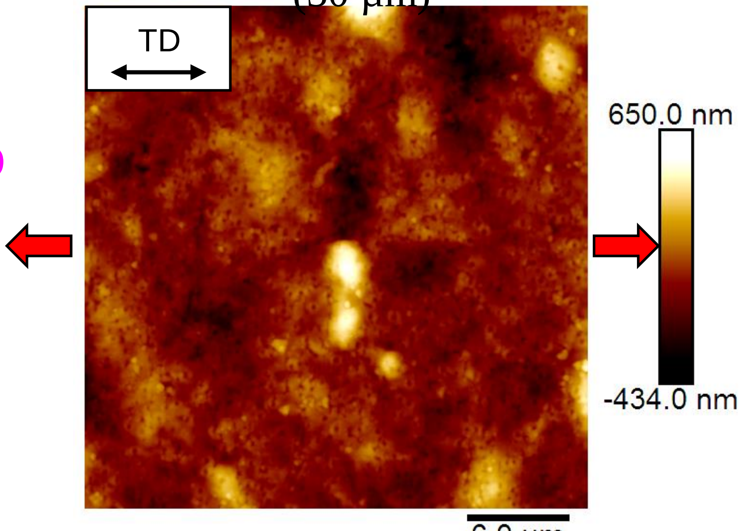
After 25% strain, Relax for 5 days (10 μm)



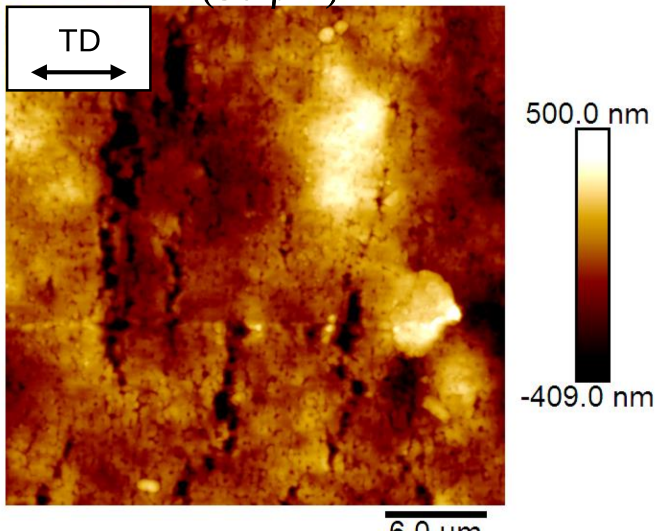
PVDF-based-4000s-TD

TD

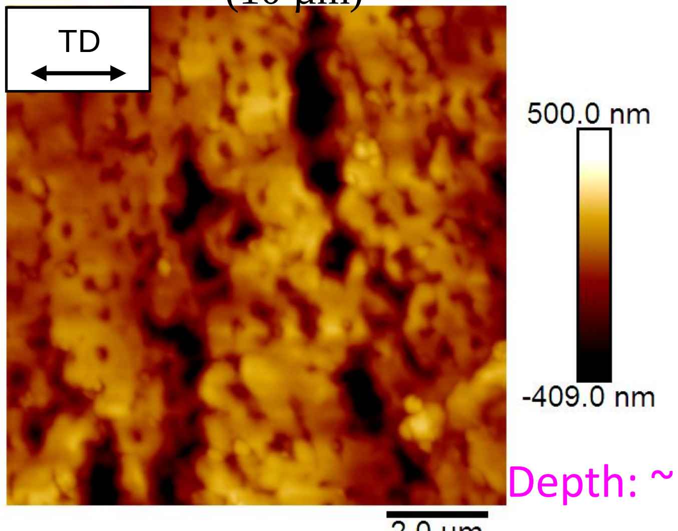
Before Strain (30 μm)



After 25% strain, Relax for 5 days (30 μm)



After 25% strain, Relax for 5 days (10 μm)



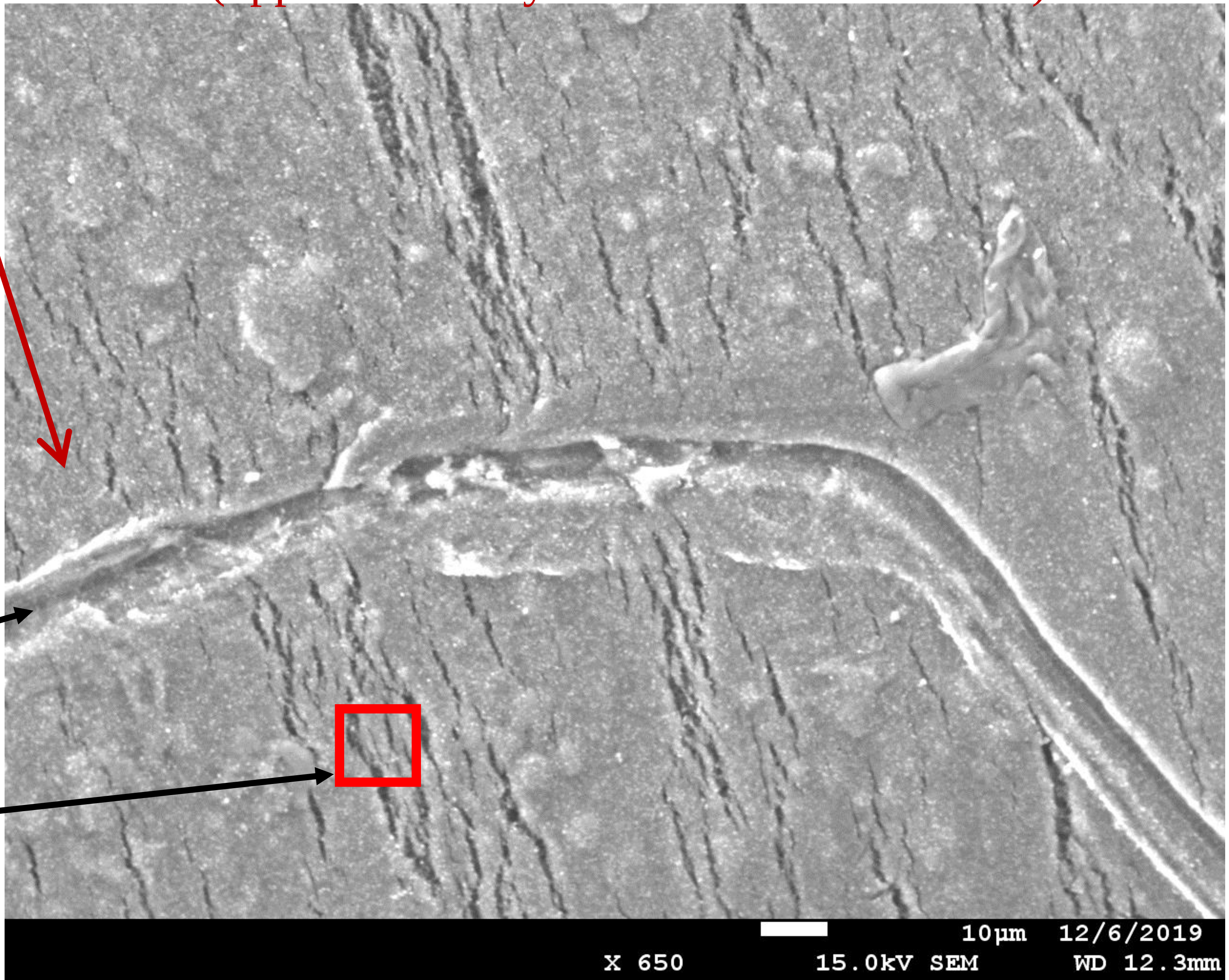
Depth: ~1 μm

PVDF-based 4000 h (A3 + water spray) after being stretched in TD, then relaxed for ~ 25 days

Secondary Electron Image

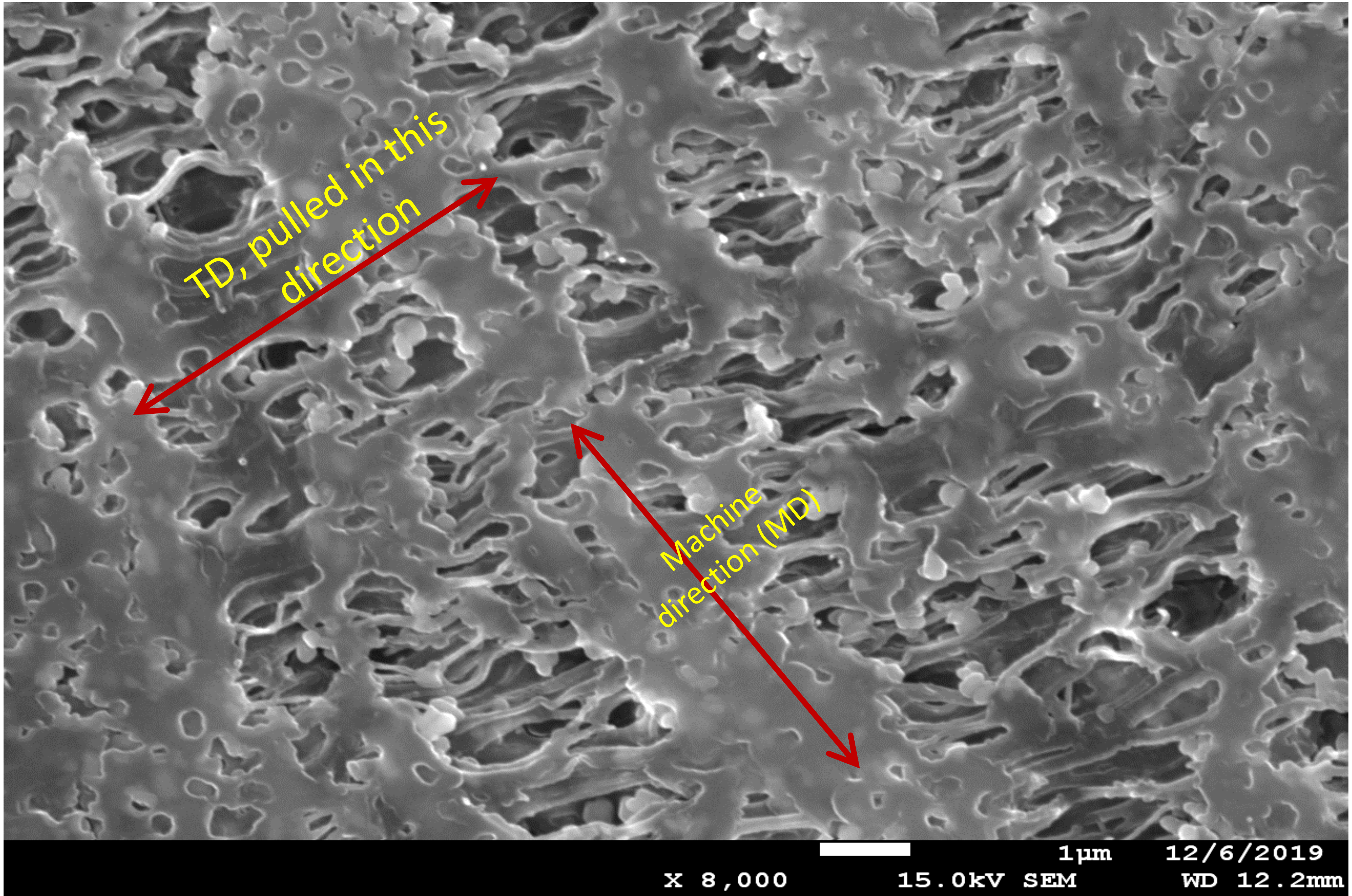
(upper secondary electron in-lens detector)

SEM Images



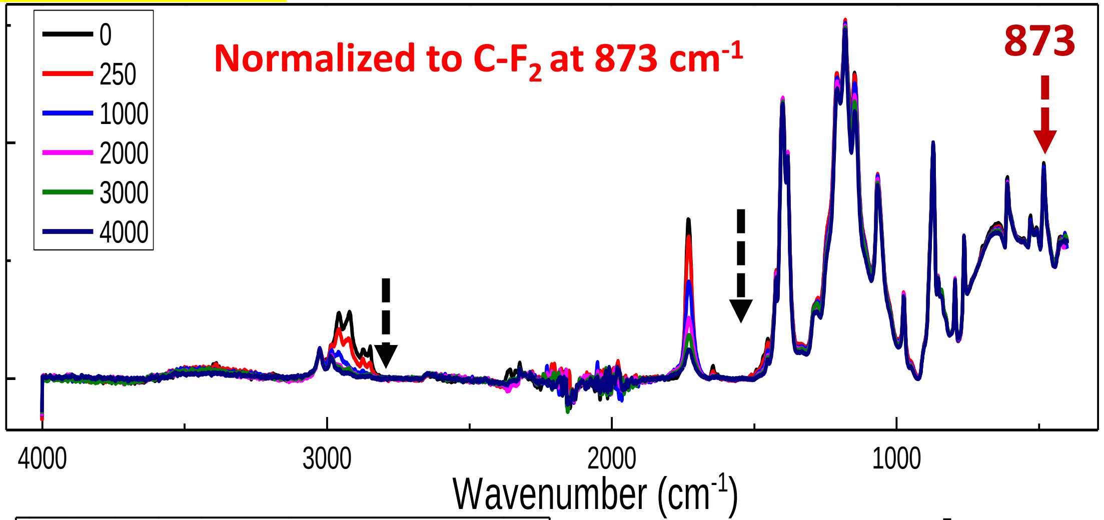
PVDF-based Backsheet 4000h+ Water Spray (TD)

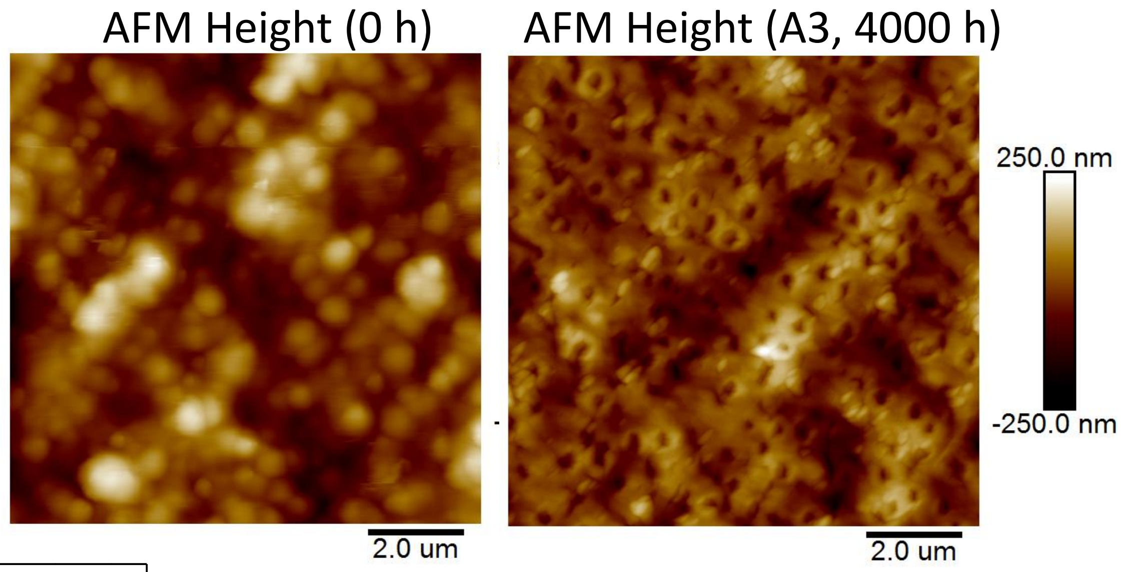
SEM Images

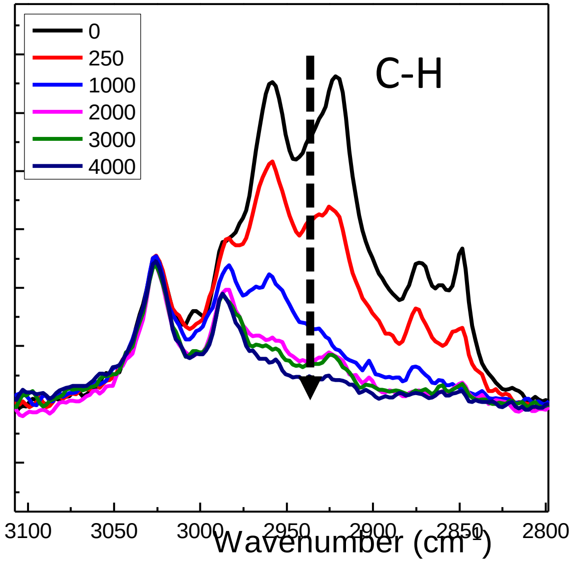


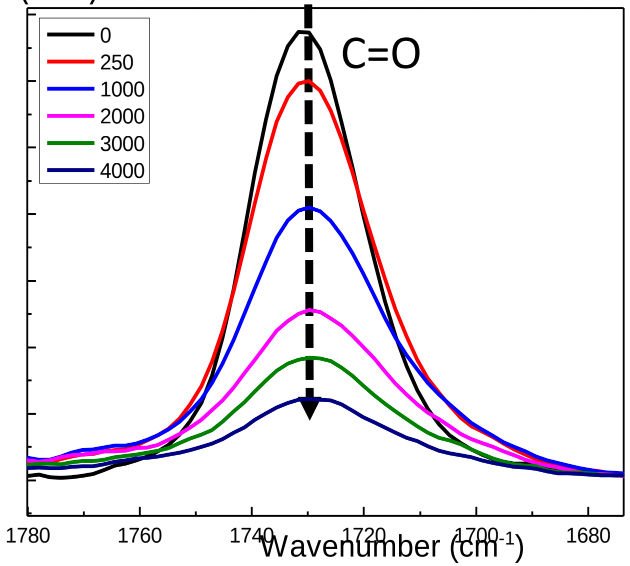
ATR-FTIR Spectra of PVDF-based Backsheets after A3 Exposure (Surface)

PVDF-based-FTIR



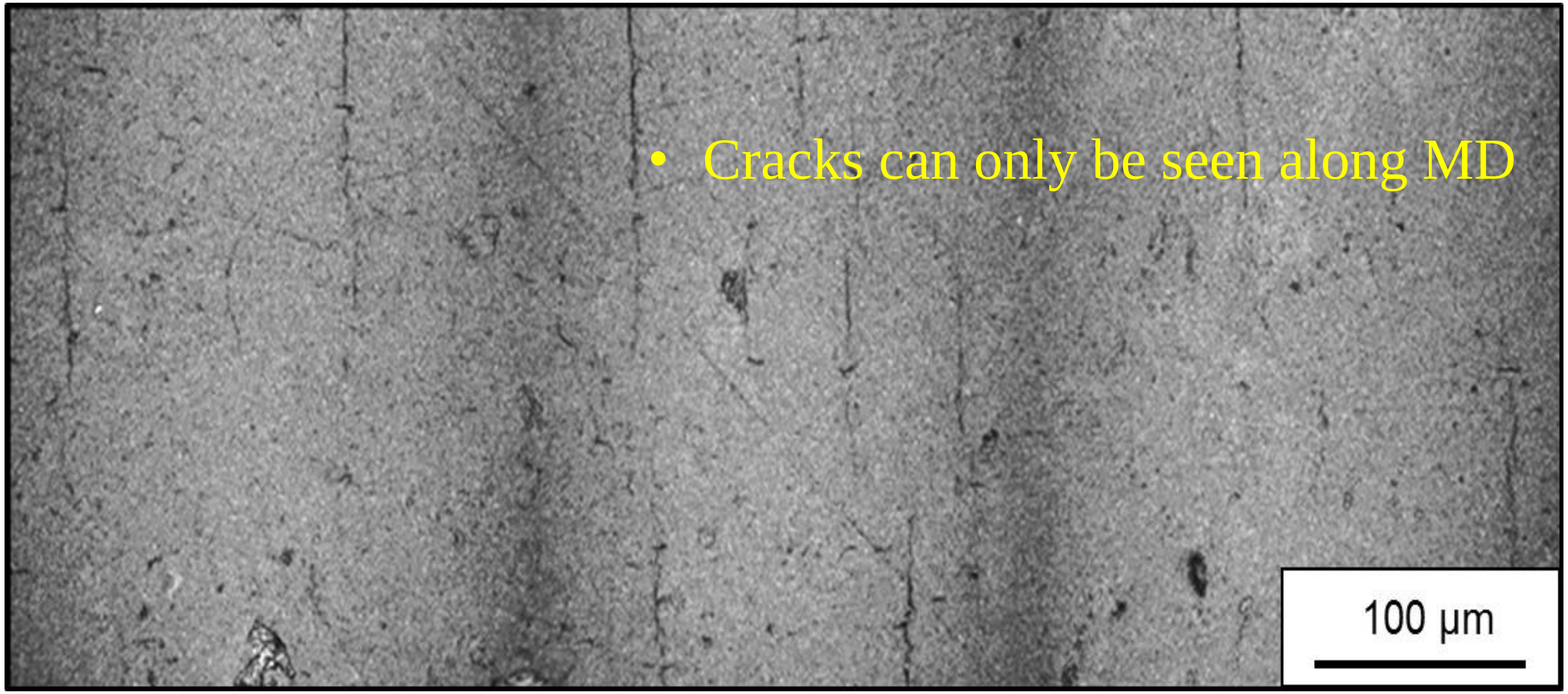






- Substantial loss of acrylate components on the exposed surface of PVDF-based backsheet

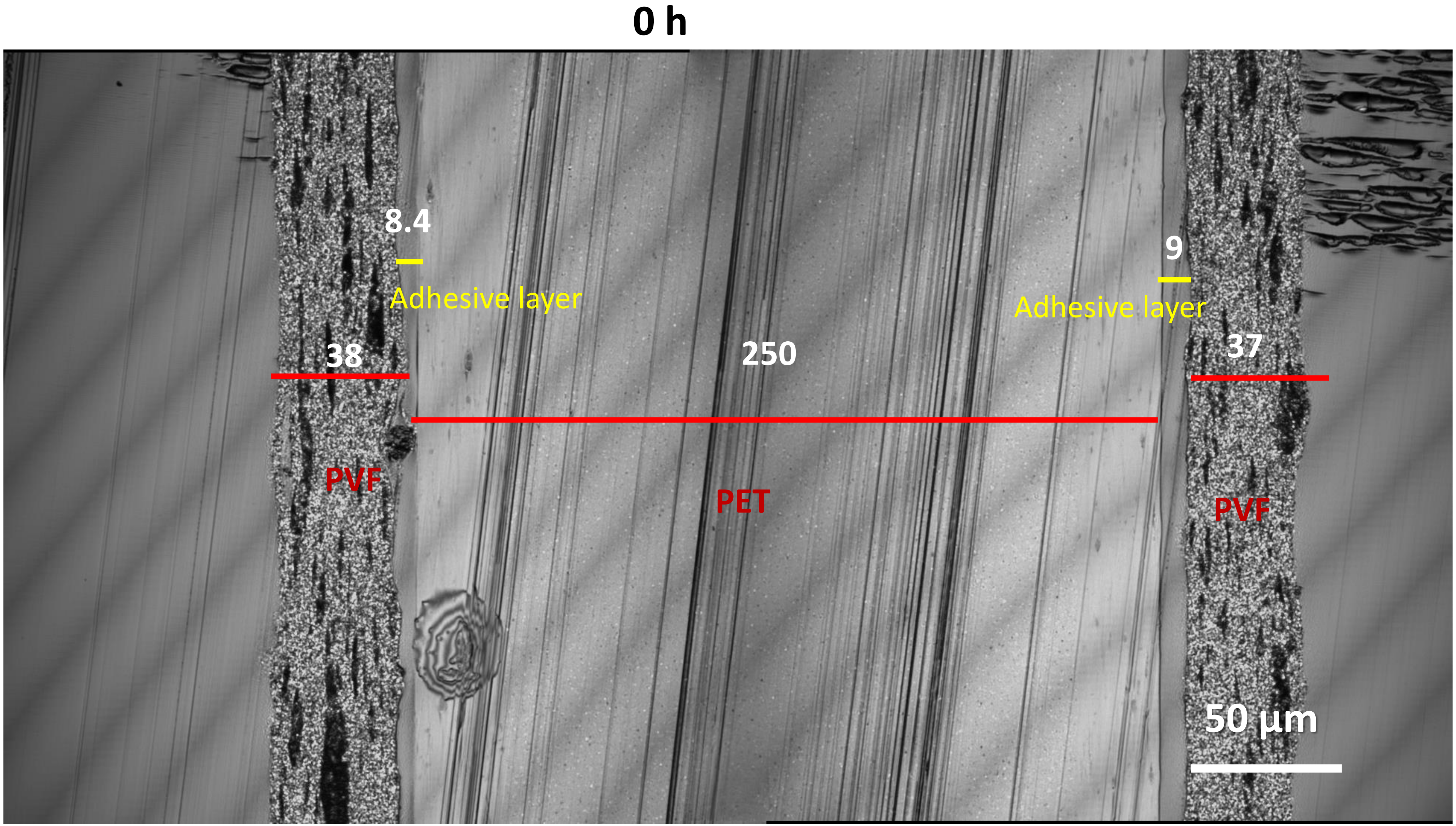
Fragmentation Test on Fielded PVDF Backsheets from Retrieved Modules in Arizona for 7 years (TD sample)



- *This field sample showed cracks locally near busbar, along MD.*
- *No cracks were observed in this region before stretching.*
- *Cracks were observed along MD at ~ 5%.*

- Fragmentation test has successfully predict the cracking propensity of this PVDF backsheet in field modules (for regions under cells without original cracks).
- The results also indicated that A3 4000 h with water spray didn’t create comparable aging for PVDF backsheet as 7 years of Arizona module condition did.

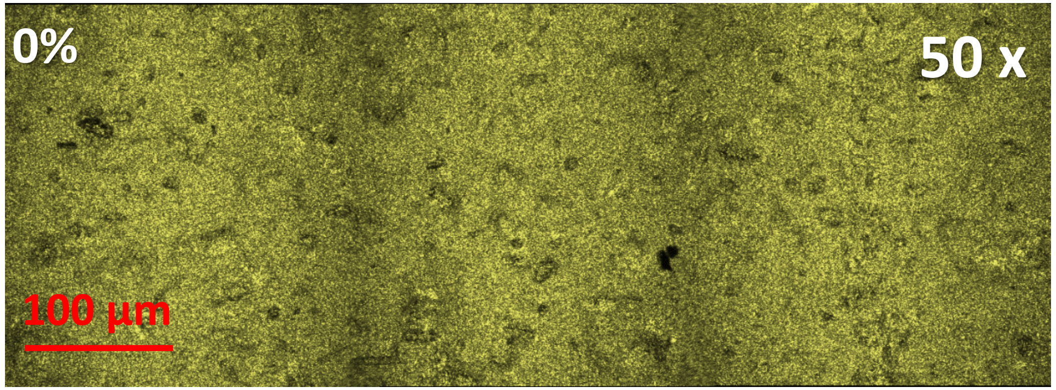
4. Backsheet Characterization (LSCM): TPT

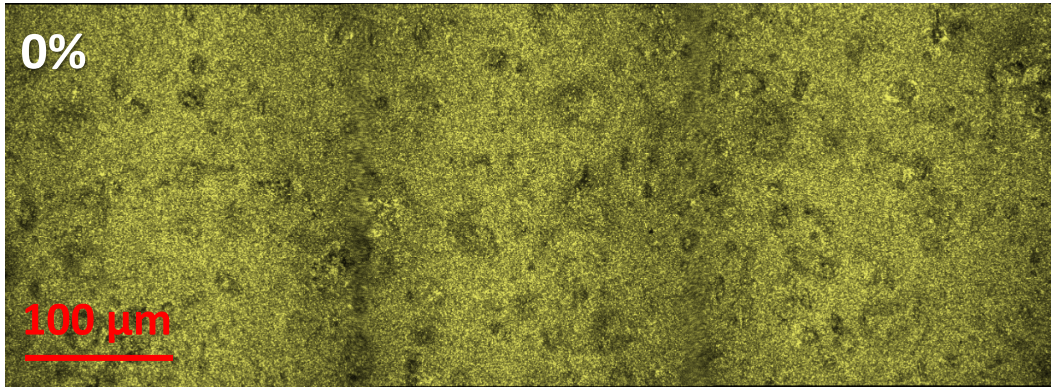


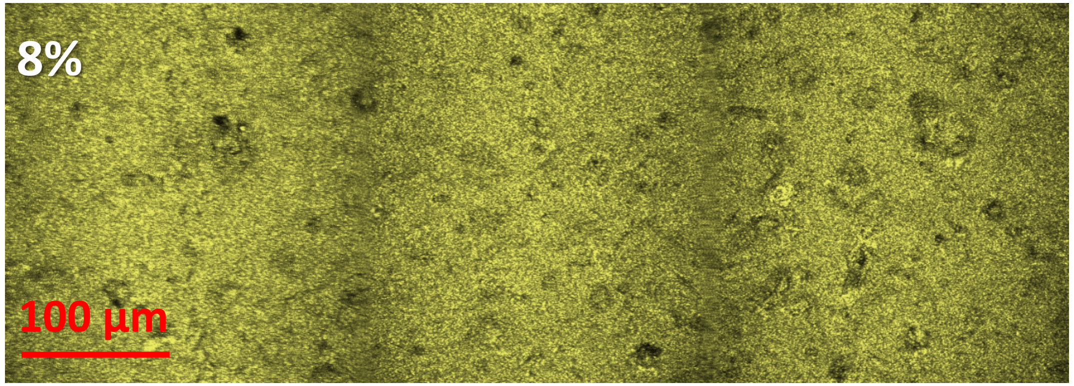
TPT

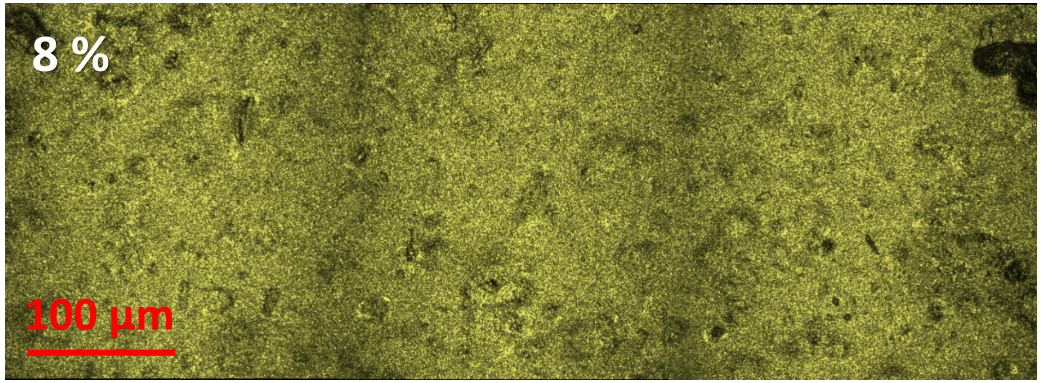
TPT (1000 h, MD)

➢ TPT (1000 h, TD)

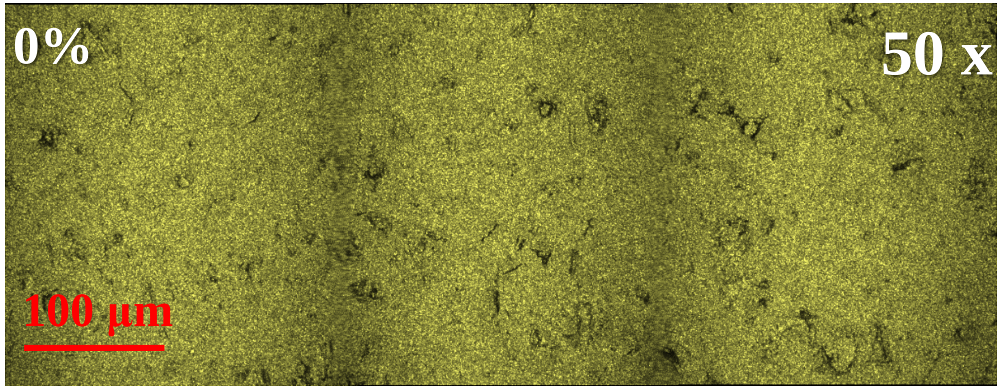


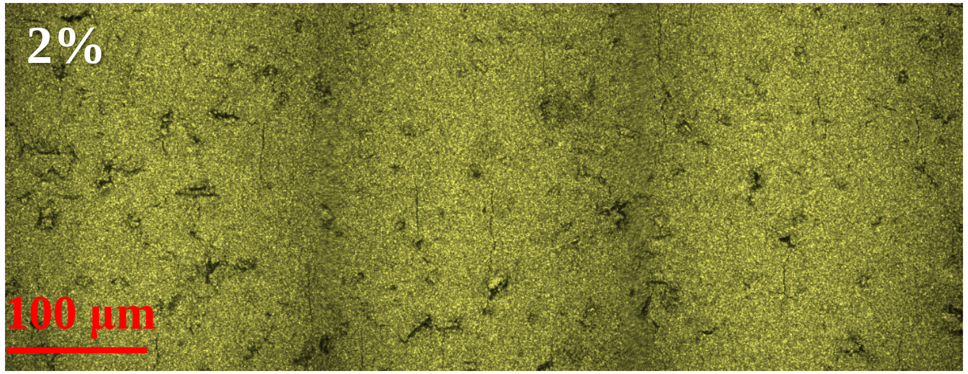


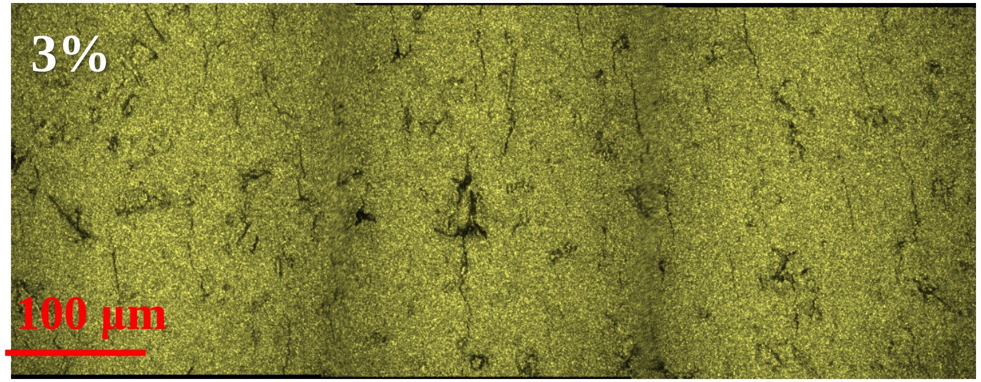


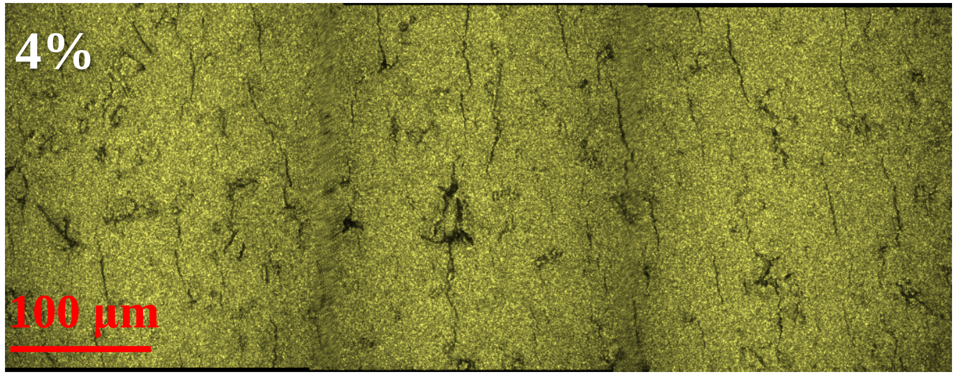


TPT (4000 h, MD, water spray)



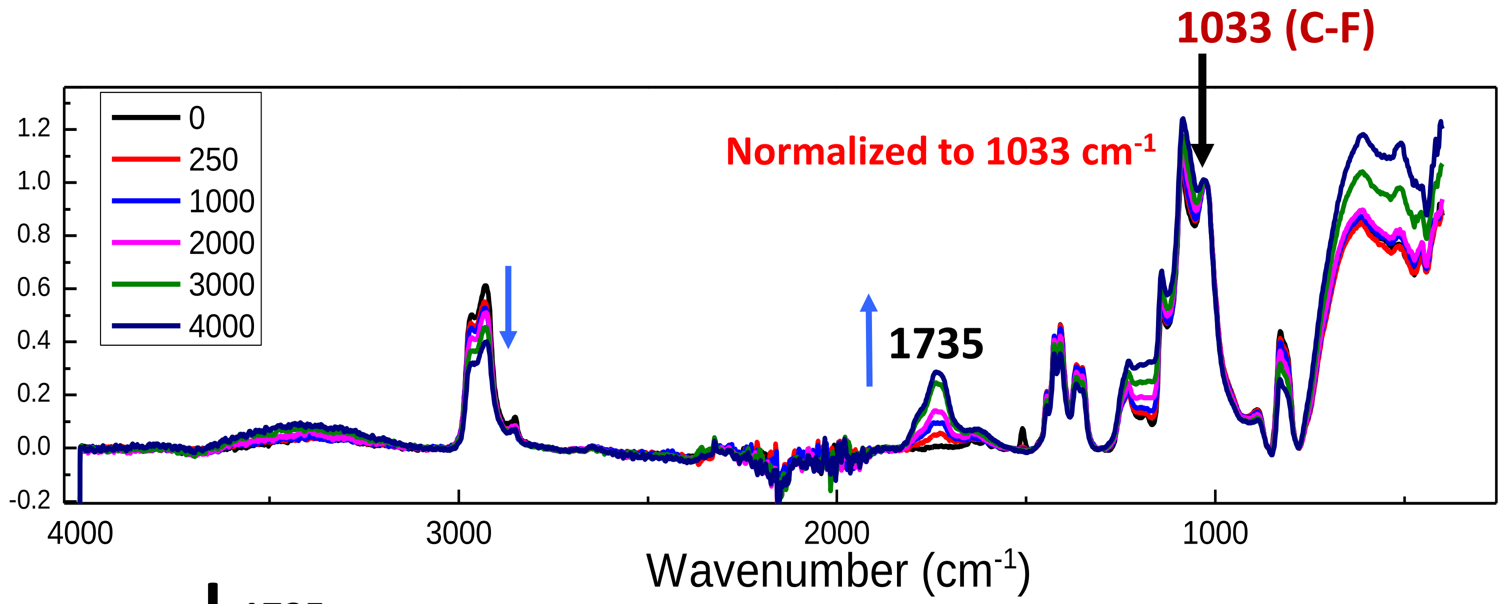


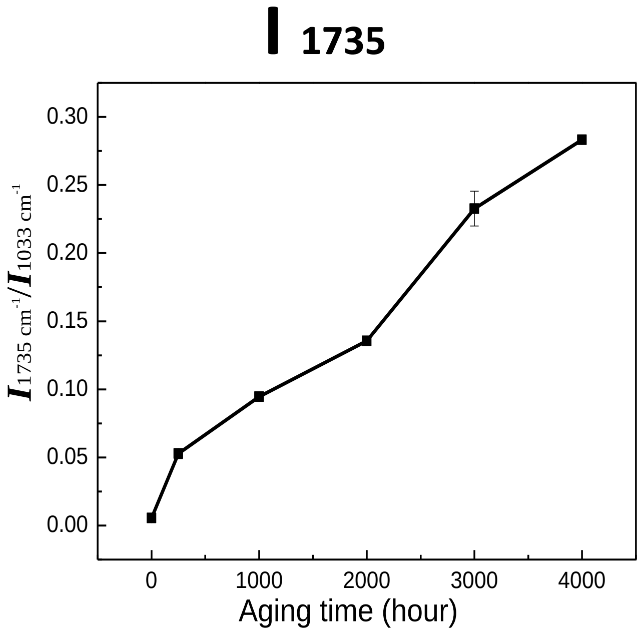


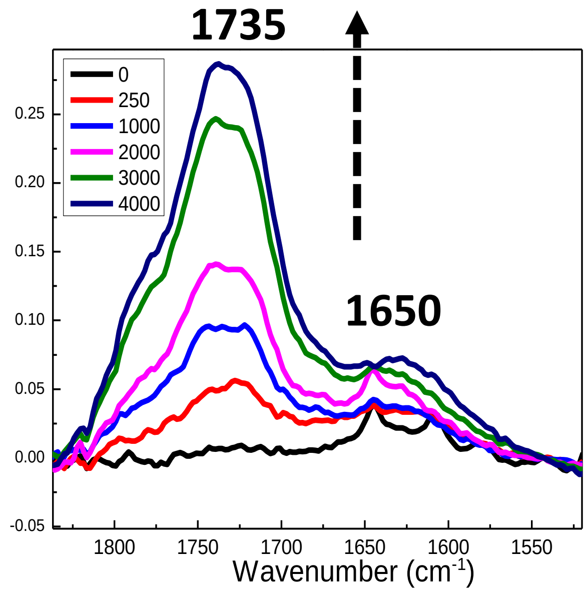


Surface cracking was observed for TPT after fragmentation test at low strains (<5 %). Is it possible that A3, 4000 h with water spray is overstressed? Or the surface cracks wouldn't not propagate into the TPT bulk? We are working on answering these questions.

ATR-FTIR Spectra of TPT Backsheets after A3 Exposure (Surface)

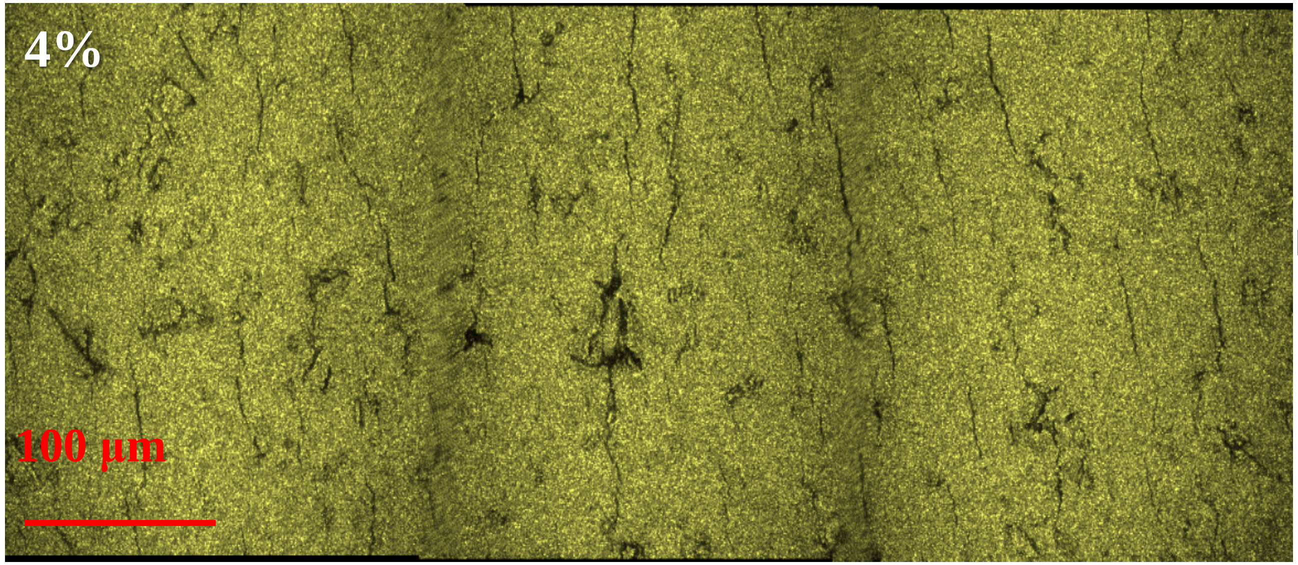






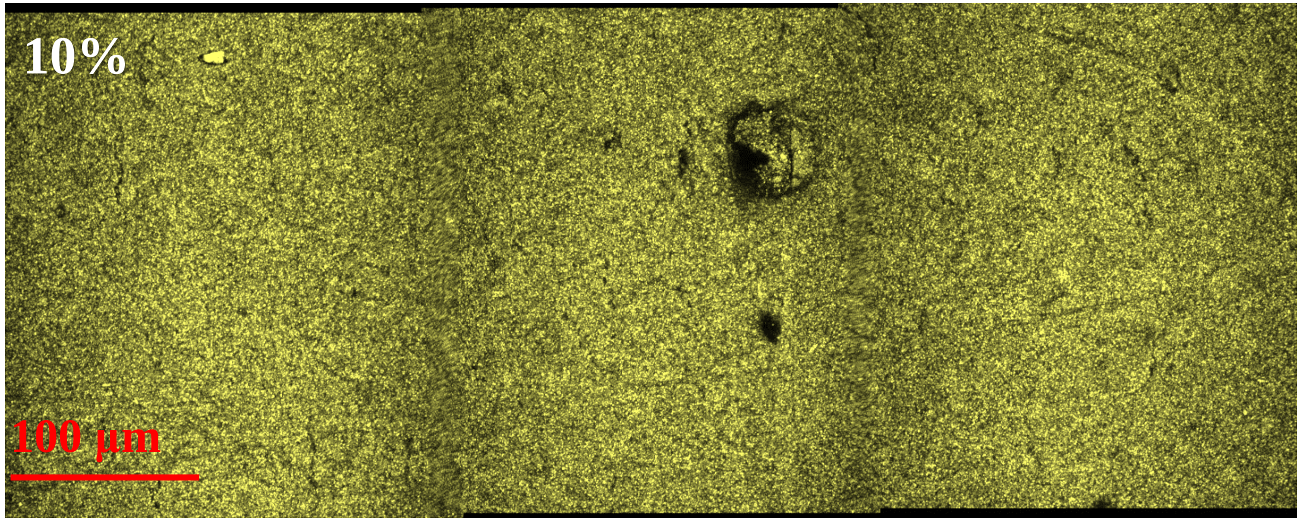
- Carbonyl formation was observed on the aged PVF surface.

- TPT (A3, 4000 h, MD) under Strain LSCM



A3

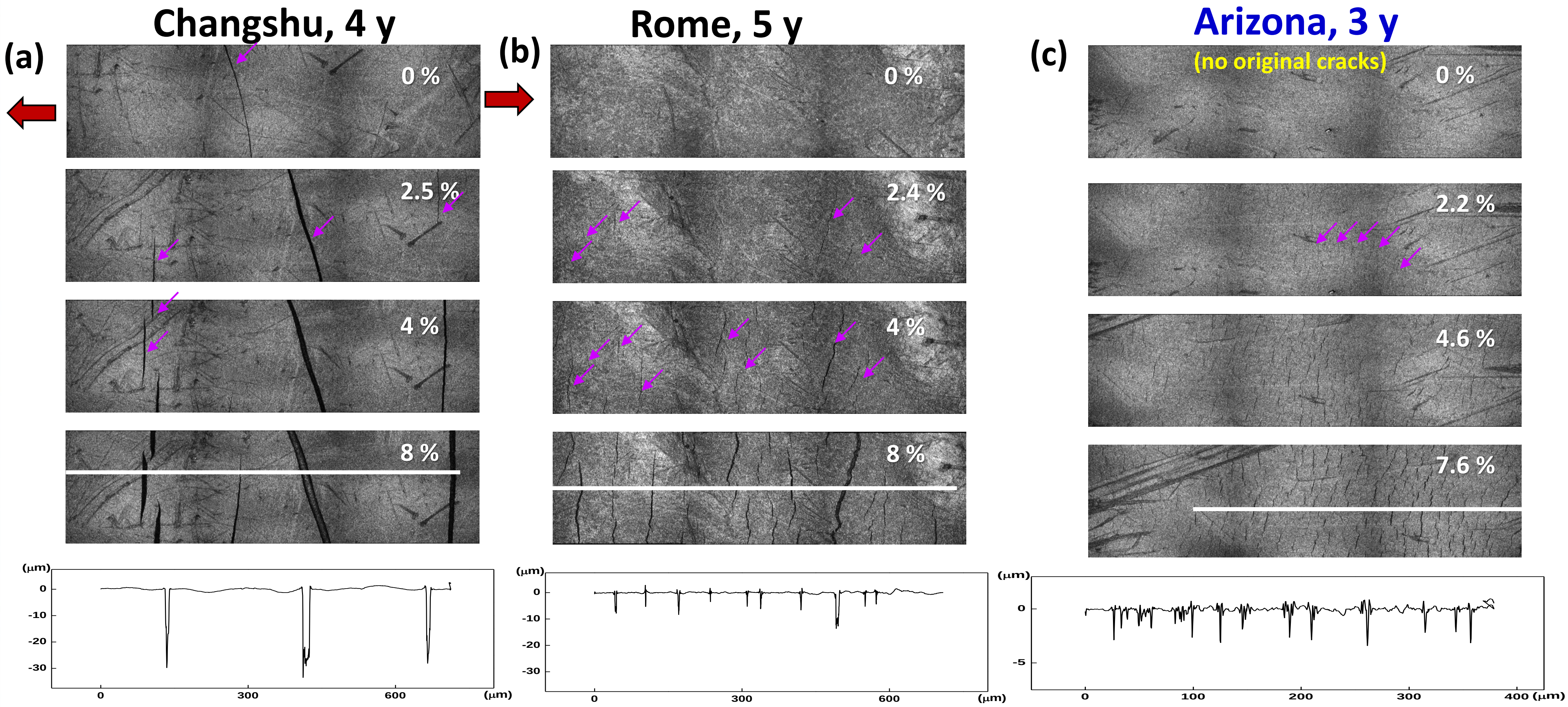
- TPT Field Sample (28 y, Sacramento, CA) under Strain



Field

- Compared to some field conditions, A3 for 4000 h may be over-stressed for surface degradation. We will continue to work on answering these questions.

Fragmentation Test on Fielded AAA Backsheets from Retrieved Modules Exposed to Different Climates



- *Under higher strains, cracks grew wider and deeper; new cracks also formed.*
- *Fragmentation test has successfully predicted the cracking propensity of AAA in the field modules (for regions under cells without original cracks).*

Summary

- Fragmentation test is simple and promising for surface mechanics evaluation and prediction for the cracking propensity of backsheets. However, it still needs further validation by materials with known performance.

- The results not only help to understand the quantitative relationship between degradation and cracking, but also can be used to assess if the accelerated exposure condition is appropriate compared to the field exposure.