Advanced methods for discovering PV module process optimization potentials and quality control of encapsulation materials

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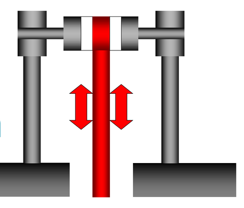
Introduction and Objectives

- Peroxide induced cross-linking of ethylene vinyl acetate (EVA) – encapsulant during PV module lamination → **Thermo-mechanical stability of EVA**
  - Time and energy consuming, discontinuous module lamination process
- Thermo-mechanical properties of EVA films have significant influence on lamination process of PV modules → **Inadequate processing** of the EVA film can cause **severe problems during PV module lamination** like exorbitant expansion, deformation of backsheets, dislocation of cells, breakage of interconnectors and wrinkles in the module
- **Main objective: Comprehensive understanding of changes of the thermo-mechanical properties before and during PV module lamination process**
  → Base for material related process optimization

- **Dynamic Mechanical Analysis (DMA)**
  - Characterization of cross-linking process
  - Shear mode, Sinusoidal load at 1Hz, circular specimen
  - Temperature and isotherm scans
    - Start: 25 to 225°C with 3K/min
    - 130-170°C, 10°C Interval



- **Thermo-mechanical Analysis (TMA)**
  - Measurement of coefficient of thermal expansion (CTE) in tensile mode
  - Temperature scan
    - 25 to 70°C with 2 K/min

- **Materials**

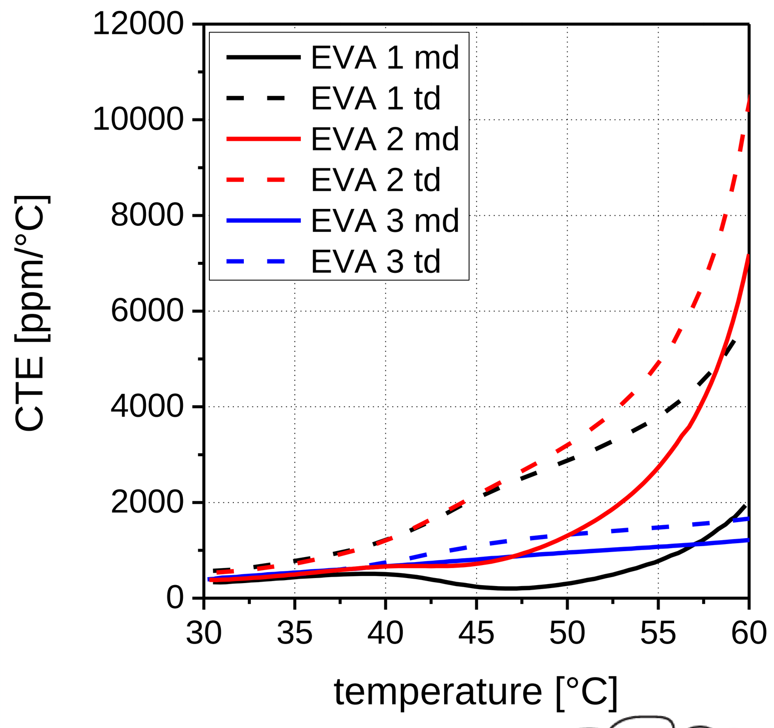
	Type	Manufacturer
EVA 1	Fast cure	A
EVA 2	Ultra-fast cure	A
EVA 3	Fast cure	B

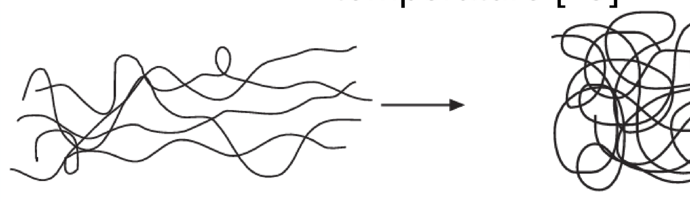
- **Production of partially cured EVA samples under relevant processing conditions**
  - Lamination temperature: 146°C
  - Cross-linking times: 300, 360, 480, 600, 720, 1200s

Results

Quality control of EVA – Thermal expansion behavior during lamination

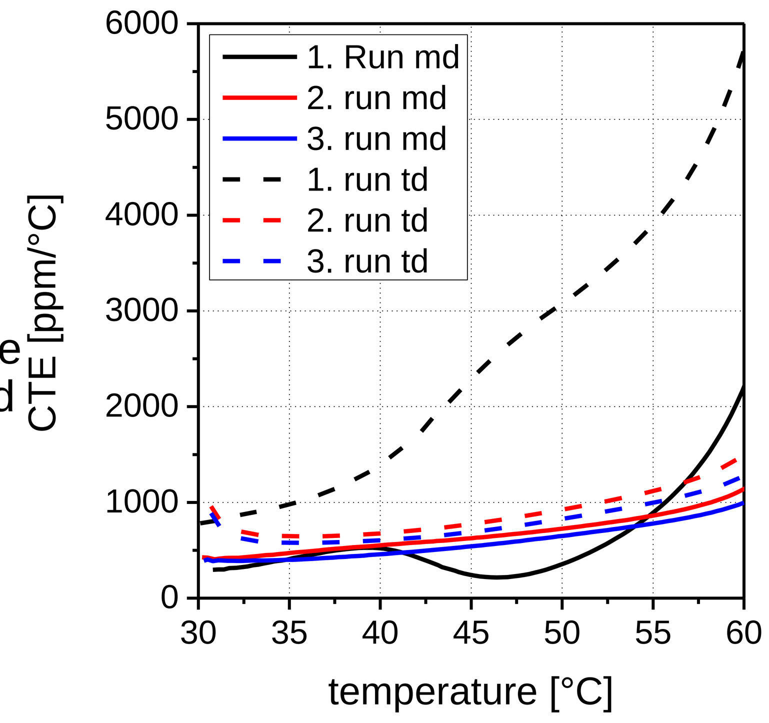
md=machine direction
td=transversal direction





Relaxation of molecular orientations [1]

- **Increasing thermal expansion with temperature**
  → Relaxation of molecular orientations
  → Bigger expansion in td due to higher degrees of freedom
  → Shrinkage in md direction caused by melting of secondary crystals, which were formed during storage at slightly elevated temperatures (~ 40°C)
- **Strong anisotropy and enhanced thermal expansion of EVA 1+3**
  → Strong molecular orientations in md due to too fast drawing off speed during film extrusion
- **Significantly lower thermal expansion of EVA 2**
  → Less induced molecular orientations during film processing and therefore less relaxation effects



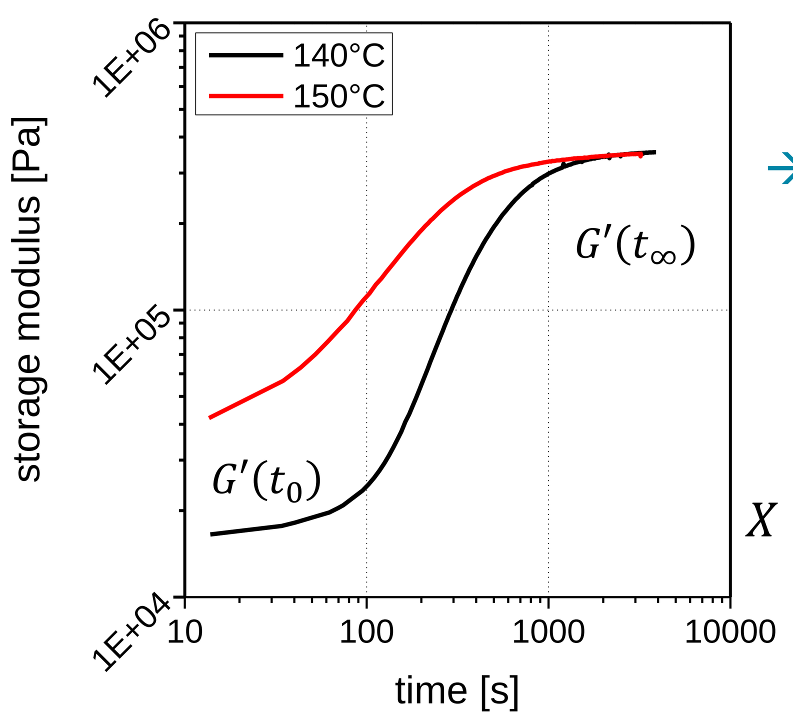
EVA 2:
Sheet of 150 x 100 cm expands to 183 x 132 cm at 60°C

- **Relaxation of orientations**
  - First heating run gives information on the current state of a polymer, including the thermal and mechanical history [1]
  - 2nd and 3rd heating run of same specimen clearly indicate irreversible orientation effects induced by film extrusion process
  - Exorbitant expansion and anisotropic behavior can cause problems during PV module lamination

Wrinkles on PV module backsheets due to excessive anisotropic shrinkage

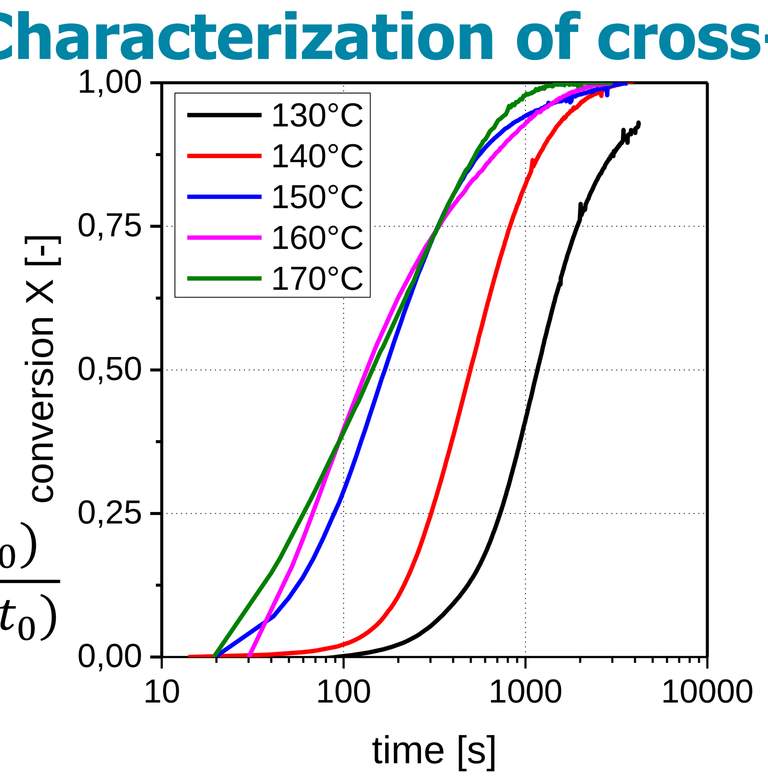
Characterization of cross-linking process

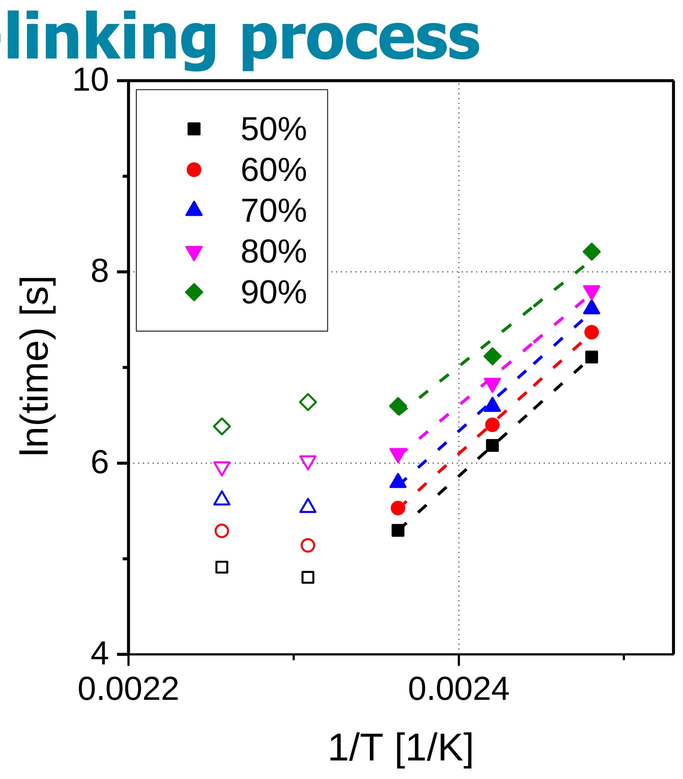
Isotherm scan



→**Scaling by calculation of conversion rate X**

$$X = \frac{G'(t) - G'(t_0)}{G'(t_\infty) - G'(t_0)}$$



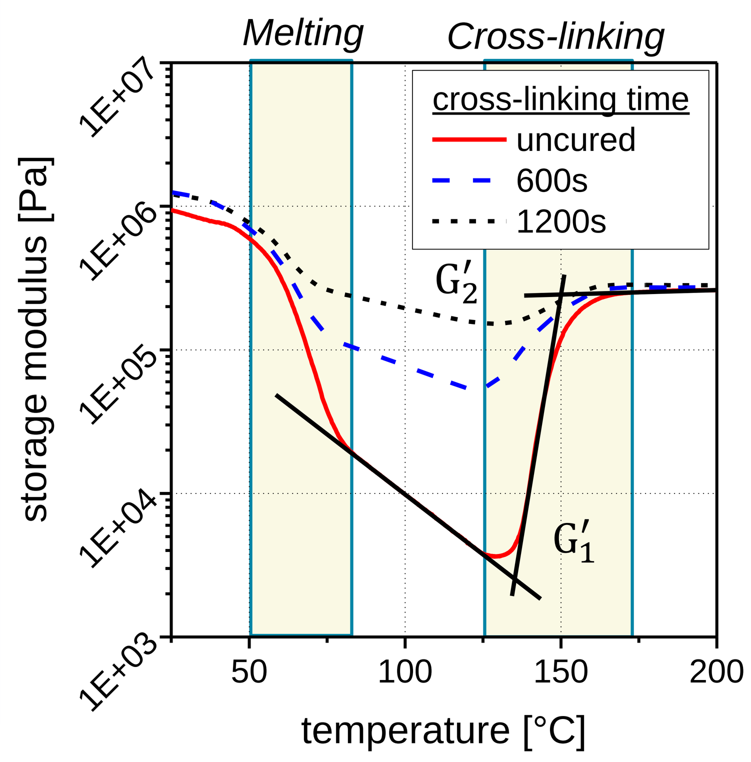


- **Derivation of optimum processing times and parameters using Arrhenius plot**
  → Activation energy of 125±7 kJ/mol in agreement with values found in literature [2]
  → Lamination temperatures >140°C are needed for full conversion
  → No further acceleration of cross-linking reaction by temperatures >150°C

Please note:
Lamination temperature ≠ temperature of EVA layer

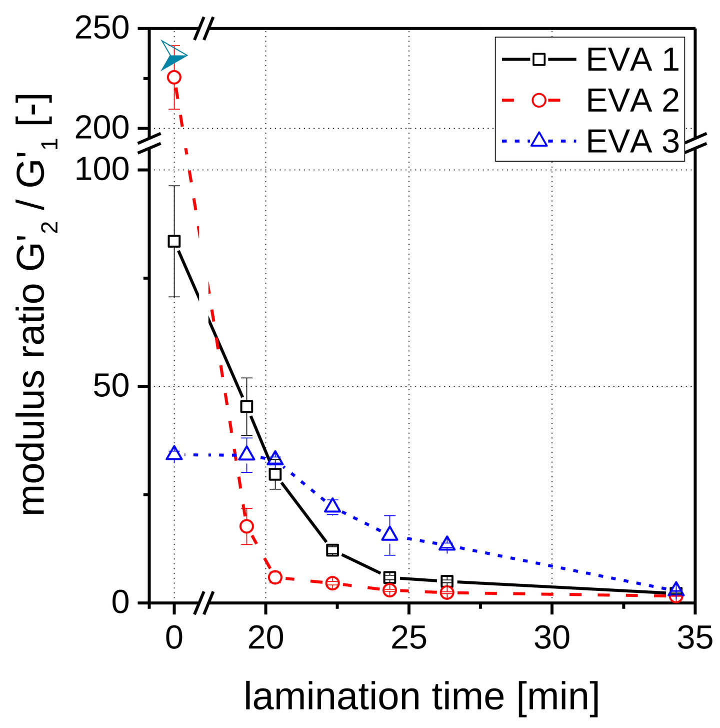
- **Increasing cross-linking density leads to higher molecular weight**
  → Increase of shear modulus in molten state
- **Scaling of measurement data necessary in order to compensate or reduce scattering due to measurement inaccuracies caused by sample preparation and handling**

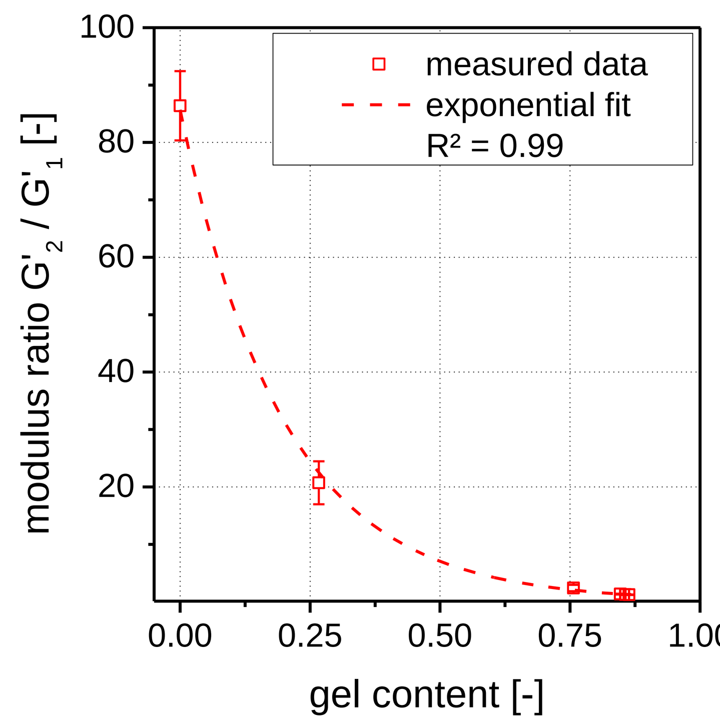
Temperature scan



→**Definition of an indicator for degree of cross-linking:**

G'_2/G'_1





- **Determination of degree of cross-linking**
  → Self referencing indicator G'_2/G'_1
    - *High reproducibility*
    - *Converges asymptotically to 1*
  → Different curing kinetics for different materials
  → Lamination temperature of 146°C not sufficient for EVA 3
  → Excellent correlation with gel content from Soxleth extraction [3]

Conclusion

- **TMA in tensile mode is a powerful tool for quality control of solar cell encapsulation materials, which allows determination of processing related effects on polymer morphology → Prevention of failures related to excessive anisotropic thermal expansion**
- **DMA in shear mode enables investigation of curing kinetics of solar cell encapsulation films → Derivation of material related process parameter optimization potentials of the PV module lamination process**
  - Determination of degree of cross-linking
  - Derivation of optimum processing temperature ranges and minimum cross-linking times

References

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