Development of a non-isothermal curing kinetics model for encapsulants in PV modules

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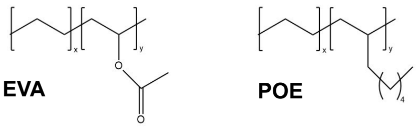
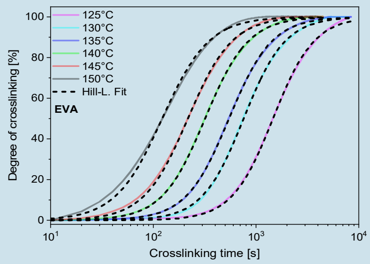
Introduction

- peroxide crosslinking ethylene vinyl acetate copolymer (EVA) and polyolefin elastomer (POE) are commonly used for encapsulation of Si-PV modules
- curing kinetics strongly dependent on temperature and time
- during lamination PV module heats up from ambient to around 150°C → **non-isothermal**
- consideration of non-isothermal crosslinking phenomena important for process optimization

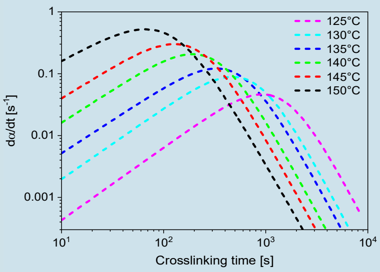


Modeling

Initial data & fitting

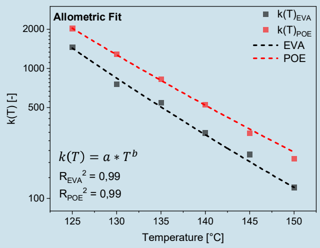


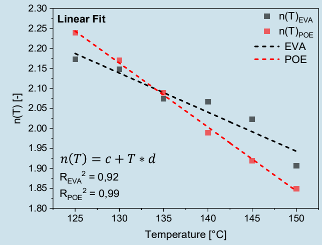
Hill-Langmuir eq.: $$\alpha(T,t) = 100\frac{t^{n(T)}}{k^{n(T)} + t^{n(T)}}$$



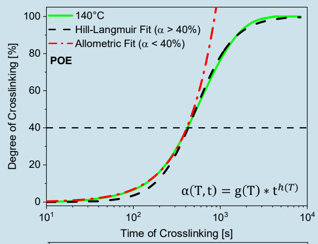
$$\frac{\partial\alpha}{\partial t}(T,t) = \frac{n(T) * k(T)^{n(T)} * t^{n(T)-1}}{(k(T)^{n(T)} + t^{n(T)})^2}$$

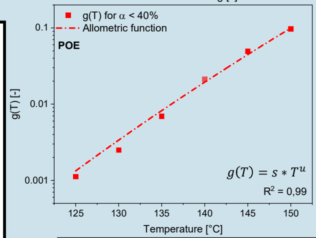
Continuous description of dataset

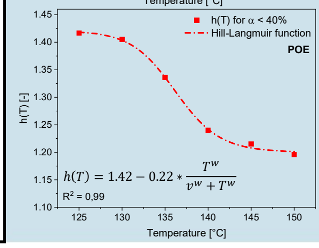




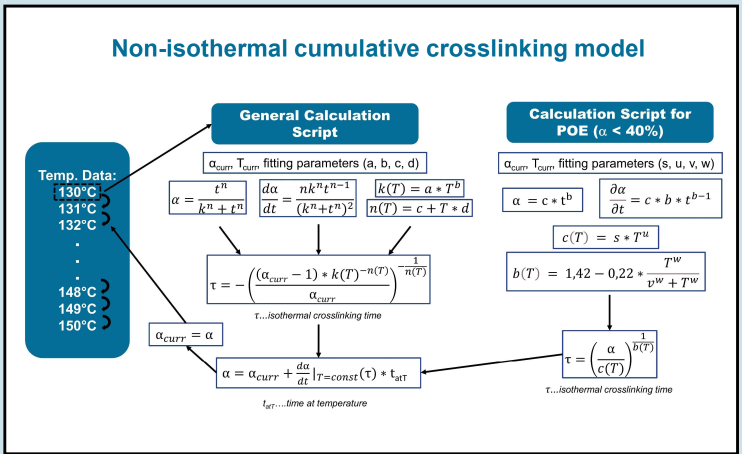
Adjustments for POE





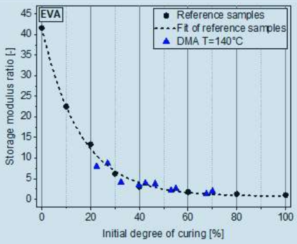


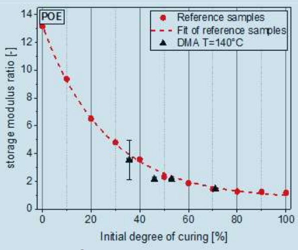
Non-isothermal cumulative crosslinking model



Results & Discussion

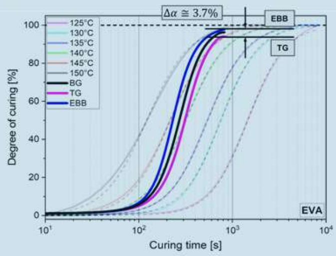
Model Validation

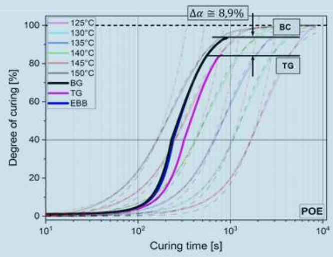




- preparation of reference samples with well-defined α
- measure increase in storage modulus using torsion DMA
- preparation of samples with unknown α, but known temperature history
- predict α using the crosslinking model and measure residual increase in storage modulus

Degree of cure in PV mini-modules





- preparation of mini-modules with attached temperature sensors on different spots (T_{lam} = 150°C, T_{lid} = 80°C, p = 800 mbar)
- bottom glass (BG), top glass (TG), bus bar on module edge (EBB)
- maximum observed differences $\Delta\alpha_{EVA}$= 3.7%, $\Delta\alpha_{POE}$= 8.9%
- lowest crosslinking degree on topside glass

Conclusions

- Hill-Langmuir equation and temperature dependent fitting parameters describe the non-isothermal crosslinking kinetics accurately
- model validation confirmed very high accuracy for both investigated encapsulant films
- applying the model on temperature data gathered during mini-module lamination revealed more inhomogeneous crosslinking of POE based laminates
- lowest degree of cure at topside glass/encapsulant interface

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