Combined experimental and simulatory evaluation of thermal and mechanical loads on PV modules

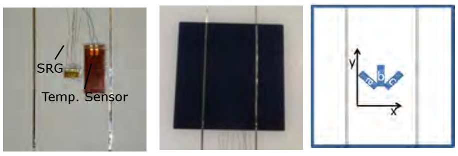
Ch. Hirschl[1], M. Granitzer[1], L. Neumaier[1], M. Spielberger[2], W. Mühleisen[1], M. Kraft[1], G. Kroupa [1], and J. Schicker[1]
[1] CTR Carinthian Tech Research, Europastr. 4/1, 9524 Villach, Austria
Contact: Email: christina.hirschl@ctr.at, T: +43 4242 56300-260
[2] KIOTO Photovoltaics GmbH, A-9300 St.Veit/Glan, Austria

Abstract

One key factor for the long-term performance degradation of photovoltaic modules is the damage of the solar cells due to cracks and micro cracks. International standards focus mainly on short- to mid-time mechanical loads, e.g. caused by snow and wind; however, in addition to this, thermal loads are of high relevance when regarding the long-time behaviour of PV installations. The named effects are complex and highly interdependent as they are affected not only by the current outdoor conditions, but also by the modules' "life history", including manufacturing. Relevant factors are the design of the PV cells, temperatures and pressures during lamination, the thermo-elastic properties of the module glass, backsheet and encapsulation materials, etc. To better understand the influence of these factors and their interrelation, which has the objective to allow for a better prediction of the long-term performance of PV modules, a dual experimental / simulatory approach was developed and implemented.

Experimental setup

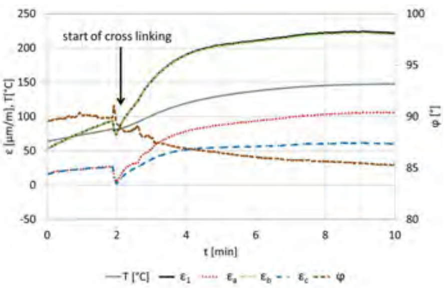
A strain resistance gauge (SRG) and a temperature sensor are fixed to the backside of a silicon cell. For the experiments, the silicon cell is integrated into a "one-cell mini module" without frame. The SRG (HBM RY89-3/350) sensor measures the elongation of the silicon cell inside the PV module in three coplanar directions a, b, c. The thermal expansion of the silicon is compensated with an additional SRG sensor.



Left: Photograph of the sensor setup
Middle: PV mini module
Right: Schematic view of the 45° rosette

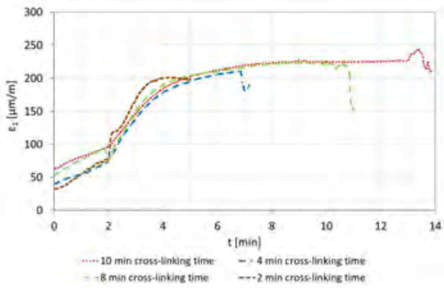
Strains during lamination

During lamination, the cell experiences large strains. The strain rises with rising temperature in the laminator. The strain parallel to the busbars (ε_b) is much higher than in the other directions.



Measured strains on a PV mini module in the three directions during an 8-minutes cross-linking process

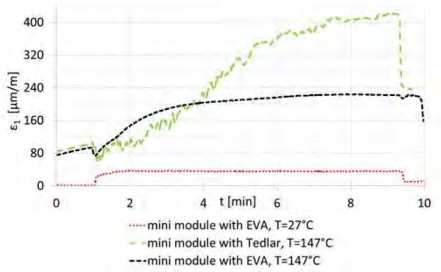
From the normal strains in the respective directions, the full plane strain tensor can be calculated and in further consequence, by solving the eigenvalue problem, the principal strain (ε_1) and the corresponding angle (φ). The variation of the cross-linking time between 2 and 10 minutes shows that the lamination time has no significant effect on to the maximum strain on the PV cell. After 5 minutes, the further increase of the strains is relatively small.



Maximum principle strain versus time for different cross-linking times

To gain deeper insights concerning the influence of ethylene/vinyl acetate (EVA) on the cell straining, the cell strains during a standard lamination process are compared to values of two alternative "lamination processes":

- lamination without heating
- lamination with Tedlar foil instead of EVA

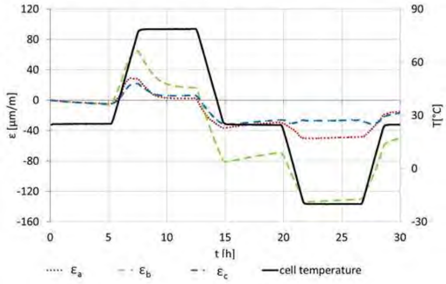


Lamination of mini modules without temperature, with Tedlar foil instead of EVA and with standard process and material

Strains during thermal cycling

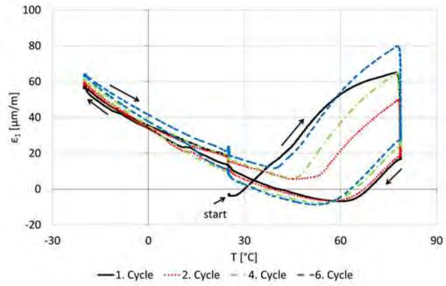
To analyse the cell straining due to thermal variations as they occur under outdoor operating conditions, the mini modules were exposed to several thermal cycles in a climate chamber. The measured strains during the first cycle can be seen in the next figure. In the high temperature period (80°C), a stress relaxation of EVA is fast and strong. After about 3 hours, the relaxation seems to come to a halt. Viscoplastic effects are much smaller at room temperature and below.

A second phenomenon that can be observed is a strong anisotropy. The strains in b-direction of the strain gauge rosette is much higher than the strains measured in a- and c-direction.



Strains in the different directions during the first thermal cycle

The first principal cell strain versus the temperature is plotted in the next figure for a number of representative cycles. It can be observed that the EVA has strong relaxation behaviour in the upper temperature range, whereas it shows no relaxation in the lower temperature range.



Hysteresis of the thermal cycle

Simulation

In order to explain the measured strain effects, first Finite Element simulations of the thermal expansion of the mini module were carried out. It turned out that, in order to simulate nonlinear strain effects as observed in the experiments, a viscoplastic model of the EVA is required, which is however not yet fully available. Nevertheless, simulations showed that by using temperature dependent parameters for the EVA, the decreasing stress in the experiments during heating can be reproduced realistically.

Conclusions

- Module lamination imposes the largest stresses and strains on the PV cells during the module lifetime due to the combination of mechanical loading by the membrane of the laminator and the large temperature changes
- Increasing lamination time does not increase the strains
- EVA is essential for the protection of the cell during lamination and temperature changes in operation
- During temperature cycling in the climate chamber, which simulates realistic operation conditions, a strong viscoplasticity can be shown at high temperature (80°C)
- The strains during thermal cycling are three times lower than during the lamination process

Acknowledgements

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