Effects of lamination condition on durability of PV module packaging and performance

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Abstract

Ten mini-modules of glass /encapsulant /backsheet structure were laminated under the condition of the same curing time and pressure, but different curing temperatures and aged in damp-heat accelerated ageing test in order to investigate the effect of temperature on the durability of PV module packaging and performance. Results show that the mini-modules using EVA as encapsulant were affected more by the laminating temperature compared to the mini-modules using modified ionomer. For EVA modules, samples with relatively low curing temperatures at 135-140°C appeared to have higher adhesion between EVA and glass, lower moisture permeability into module and better dielectric of cells than those with high curing temperatures.

Introduction

PV modules rely on the cell packaging materials to provide durability. Typical module packaging materials include encapsulants, front glass and backsheet, which are laminated together and framed to form a PV module and protect solar cells in harsh operating environments. Different types of materials and various combined lamination strategies may influence the packaging durability and thus affect module reliability. This paper investigates the effects of different lamination curing temperatures on the durability of PV module packaging and performance whilst undergoing damp-heat (DH) stress.

The effects of different lamination conditions on material mechanical and chemical properties for laminates without solar cells are studied in [1]. The curing time and temperature will influence the adhesion at interfaces between different layers as water can weaken interfacial adhesive bonds. The lamination conditions, therefore, have an impact on the rate of moisture ingress into modules. With solar cells laminated into the module, tabbing bus wires and interconnecting wires are required to transport the generated current flow. The electrical circuit is sensitive to moisture inside the module as it causes loss of passivation, electrochemical corrosion and ultimately module failure.

Moisture can enter the module from unsealed edges, the junction box, or any position on the backsheet, if it is not properly made. Based on previous experience of indoor accelerated DH tests [2], modules show no or minor power degradations usually after moisture starts to permeate inside. The power degradation will become apparent once the internal moisture exceeds some threshold level. However, there is lack of literature on the influences of lamination condition on module packaging and performance degradation, which is the focus of this paper.

In the course of laminating commercial PV modules in sizes of 0.5m-1.2m, the temperature distribution for the whole module area is likely to vary up to a few degrees. This variation may be caused by different reasons, e.g. temperature non-uniformity during the heating and cooling processes, inaccurate calibration of temperature sensors, regional temperature rise when pressure is applied, etc. Modules laminated under these occasions usually can pass initial tests as the module power would not change too much, but these issues may become more influential on module packaging and performance after a longer period of field operation.

In order to investigate the detail of the effect of temperature variation during lamination on PV performance, ten mini-modules were laminated under the same curing time and pressure, but different curing temperatures, and degraded in DH condition in an environmental chamber. The module I-V characteristics and electroluminescence (EL) images have been measured and studied during the course of ageing procedure.

Experiment

A laminator of 0.8m by 1.6m working space was set up and used for this work. A few trial tests were carried out in order to calibrate the temperature profile at different positions of the working space. The size of mini-modules made is 12.5cm by 20cm with an 8cm by 15cm multi-crystalline silicon (multi c-Si) solar cell. The temperature variation across the sample was reduced to a minimum and the repeatability of samples made during different lamination cycles was tested to be good.

The structure of laminated mini-modules made at CREST is shown in Figure 1. It has five layers, i.e. front glass /encapsulant /solar cells /encapsulant/ backsheet, but no frames or sealants. All the materials are commercially available from the PV market. The glass front layer is 3.9mm thick low iron float, fully tempered glass. Two types of encapsulants are used including standard 600μm thick ethylene vinyl acetate (EVA) and modified 300μm ionomer. Comparing to EVA, the modified ionomer has advantages of reduced moisture permeability, increased resistivity, improved adhesion to glass, etc. The backsheet is a tri-layer insulating polymer consisting PET/PET/primer layer. The solar cells used are 1.8W multi c-Si cells. Figure 2 shows one of the mini-modules used in this work.

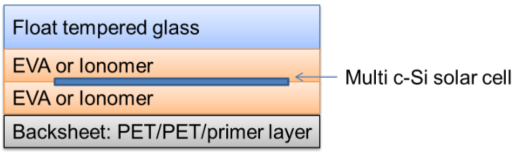

Fig 1: Structure of mini-modules made at CREST.

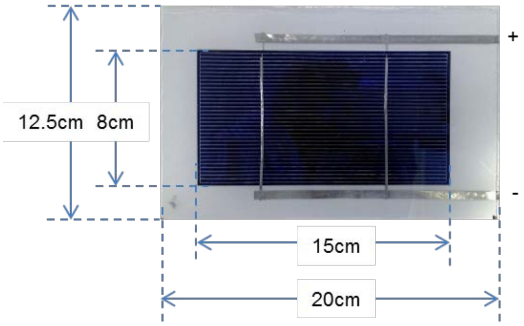

Fig 2: Picture of a laminated mini-module.

The materials of encapsulants and backsheet were stored in a desiccator and kept in dry condition prior to lamination. Glass was cleaned and dried before use. All mini-modules of glass /encapsulant /backsheet structure were laminated for ten minutes under 600 mbar pressure. Different curing temperatures were applied for samples with EVA and Ionomer and are summarized in Table I below.

Table I: Summary of laminated mini-modules.

Sample ID	Encapsulant material	Curing temperature (°C)
T140-1	EVA	140
T140-2	EVA	140
T135-1	EVA	135
T135-2	EVA	135
T135-3	EVA	135
Iono-150	Ionomer	150
T145	EVA	145
T146	EVA	146
T149	EVA	149
Iono-140	Ionomer	140

The laminated mini-modules were placed in an environmental chamber and aged under 85°C temperature and 85% relative humidity for durability testing. These samples do not have frames, sealants or junction boxes, which allows faster moisture permeation into modules, especially from the sides [3]. Samples were measured before ageing and after 150, 300, 500, 650, 800, 1000 hours of ageing. At each time interval, visual inspection was carried out and I-V curves and EL images were measured for each device.

Durability of Packaging

The visual inspections for aged samples are described in this section. A typical delamination pattern happened at sample corners and edges, as shown in Figure 3, was observed for the samples using EVA as encapsulant after 300-800 hours of DH ageing. This delamination occurred at the interface between front glass and EVA as it has weak adhesive bonds. The interfaces of EVA/EVA and EVA/backsheet have much stronger adhesion than the glass/EVA interface, therefore no delamination was observed between these layers. Moreover, no obvious delamination was observed for the samples using modified ionomer as encapsulant due to its inherent properties of reduced moisture permeability and improved adhesion to glass.

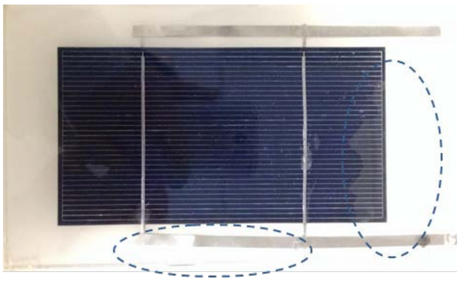

Fig 3: Delamination observed at corner and edge of sample.

Table II: Summary of delamination details for samples with EVA encapsulant.

Sample ID	Curing T (ºC)	Severity after 800h	Started after how many hrs
T135-1	135	Appeared in corners	800
T135-2	135	Appeared in corners	650
T135-3	135	Appeared in corners	650
T140-1	140	Appeared in corners	650
T140-2	140	Moderate in corners	500
T145	145	Severe in corners	500
T146	146	Severe in corners	500
T149	149	Severe in corners and edges	300

Considering the different curing temperatures and the delamination severity for the EVA mini-modules, an interesting correlation was observed and summarised in Table II. It appears that the curing temperature has a large influence on the delamination between glass and EVA for the mini-modules used in the experiment. After 800 hours of DH ageing, the most significant case of delamination was observed around sample corners and edges for the sample with the highest curing temperature of 149ºC. The samples with the lowest curing temperature of 135ºC seem to be more reliable and this delamination only started to appear around sample corners after 800 hours. Another interesting observation is that the delamination started after 300-500 hours of ageing for samples of curing temperatures ≥145ºC, after 500-650 hours of ageing for samples of curing temperature 140ºC and after 650-800 hours of ageing for samples of curing temperature 135ºC. The high curing temperature might already overcooked the samples which led to early delamination.

Degradation of Module Performance

Degradation behaviours of P_{MPP}, I_{SC}, V_{OC} and FF for the ten mini-modules, as shown in Figure 4, are discussed in this section.

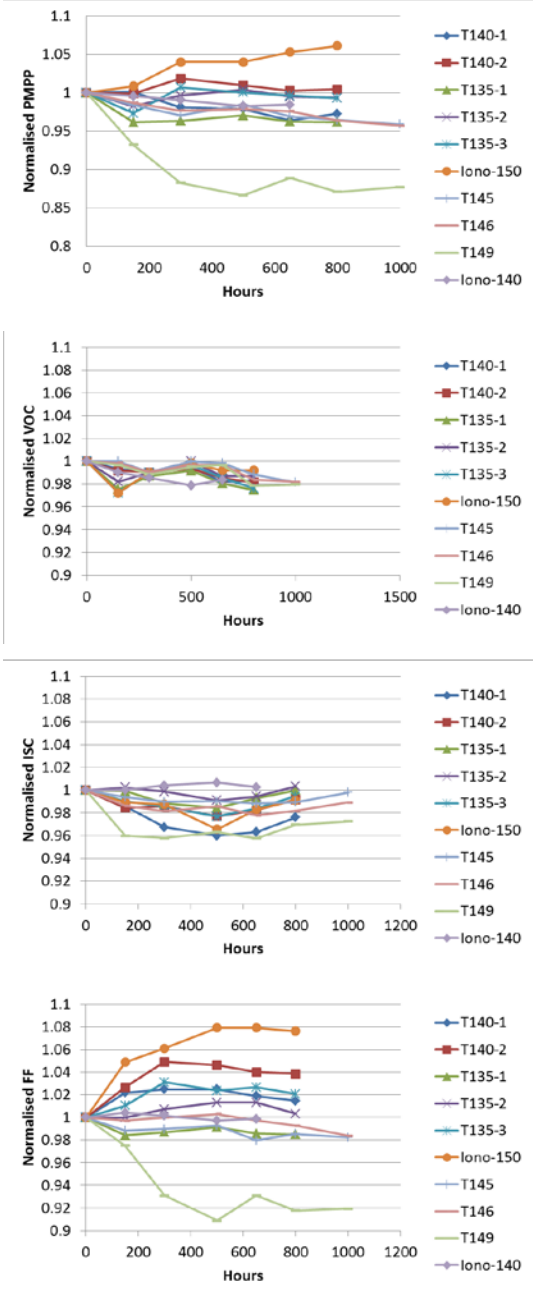

Fig 4: Degradations of P_{MPP}, V_{OC}, I_{SC} and FF (from top to bottom) over time for the ten mini-modules.

The overcooked sample (T149) showed the largest reduction in power by 13% after 1000 hours. This power loss was mainly due to FF loss about 8% as indicated in the bottom plot of Figure 4. Its V_{OC} and I_{SC} just showed minor degradations of 2% and 3%, respectively. Except for the Sample T149, the other samples didn't show large degradations in power, i.e. between 0 and 4.5%. One sample with modified ionomer as encapsulant (Iono-150) laminated at 150°C even showed increases in power after ageing. Also, these increments were mainly contributed by the increases of FF.

Considering the EVA samples, minor changes were observed for V_{OC} after ageing, which were between 1% and 2%. Similarly, I_{SC} showed small degradations between 0 and 3%. FF showed similar degradation behaviours as P_{MPP} with only Sample T149 degraded by 8%, while the others degraded less than 2%. Plotting the power reductions against curing temperatures for the eight EVA samples, as shown in Figure 5, the degradation retains at similar level with curing temperature in the range of 135-145°C and tends to increase nonlinearly with increasing curing temperature ≥145°C.

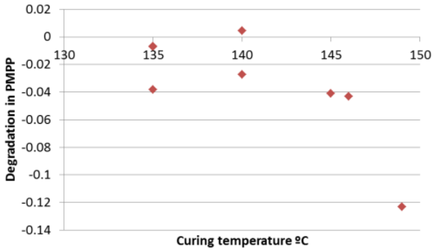

Fig 5: Degradations in P_{MPP} versus curing temperature for samples using EVA encapsulant.

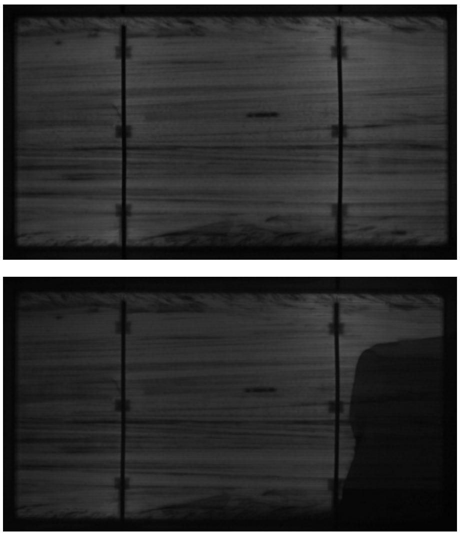

Fig 6: EL images of Sample T149 before ageing (top plot) and after 500 hours DH ageing (bottom plot).

Investigation of EL Images

EL images before and after 500 hours DH ageing for the overcooked Sample T-149 are show in figure 6. Deterioration was observed in the bottom right corner and bottom edge of sample due to moisture ingress into module. No significant changes in EL were observed for the other samples as the power degradations were minor.

Conclusions

Ten mini-modules were laminated under different curing temperature ranging from 135°C to 150°C and aged in DH condition of 85°C, 85% for up to 1000 hours. The modified ionomer based mini-modules have the best durability of packaging and performance due to the material inherent advantages. The EVA based mini-modules appeared to be affected by the curing temperature significantly. Higher adhesion to glass, lower moisture permeability and better dielectric were observed for samples with curing temperatures at 135-140°C. With curing temperature greater than 145°C, samples tended to be less reliable as early delamination between glass and EVA and large reduction in power were observed.

Acknowledgements

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References

[1] Wu D., Zhu J., Betts T.R., Gottschalg R., The effect of lamination conditions on the properties of encapsulation materials of PV modules, *10th PVSAT*, Loughborough, UK, 2014.

[2] Zhu J., Gottschalg R., et al, Towards Service Lifetime Prediction of Photovoltaic Modules, *PV Module Reliability Workshop*, Golden, USA, 2014.

[3] Kempe M.D., Modelling of rates of moisture ingress into photovoltaic modules, *Solar Energy Materials and Solar Cells 2006*; 90(16): 2720–2738.