AISOVOL PROJECT: A PHOTOVOLTAIC GENERATION SOLUTION AS AN ALTERNATIVE CONSTRUCTION MATERIAL

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ABSTRACT: AiSoVol project consists on the development, manufacturing and testing in a controlled environment of a new concept of photovoltaic modules, conceived for facilitating their use as architectural elements. Thus, the modules will be fabricated by encapsulating its constituent electrical elements (cells and interconnections) with lamination techniques at low curing temperatures and using transparent thermoplastic instead of tempered glass, as well as binding materials structurally strengthened by a grid made of high-tenacity yarns, such as the ones used in sail technologies and thus avoiding the need for aluminum frames. This type of solution will provide, due to the nature of the constituent materials, lighter PV modules which can adapt easier to different surfaces. In this paper the methodology followed to define a suitable lamination process compatible to obtain reliable AiSoVol photovoltaic modules is described. Results achieved from materials and processes validation will pave the way for manufacturing the prototypes in next project phase.

Keywords: BIPV, encapsulation, polymer film, polycarbonate.

1. INTRODUCTION

At this initial phase of the AiSoVol project the focus has been put on the materials validation and its compatibility with processes involved in PV module manufacturing. Study of thermal, optical, physical, electrical and mechanical properties of several transparent thermoplastics raised the polycarbonate (PC) as best option to be used as superstrate for the AiSoVol BIPV modules. The rest of the package constituent materials are the encapsulant, PV cells, reinforcement grid made of high-tenacity yarns and the backsheet. The sublayer structure of this new BIPV product differs notably from that of conventional PV modules. What is investigated in this work is the degree of compatibility among combinations of these materials when laminated together employing the same techniques and equipment available at PV module manufacturing lines.

2. EXPERIMENTAL

Two different lines are used to study the feasibility of manufacturing reliable BIPV crystalline silicon modules based on alternative packaging materials. First approach is focused on defining the lamination process required to produce samples fulfilling minimum requirements regarding cure degree of the encapsulant, adhesion force between layers and visual aspect.
The second aspect studied in this work is the susceptibility of polymeric materials to suffer UV degradation when used for outdoor applications. This effect has been quantified by determining the evolution of the optical properties on artificially aged AiSoVol samples.

2.1. Adjustment of lamination process

The lamination parameters must be set taking into account the limitations posed by the use of polycarbonate as front cover. The polymeric films used as encapsulant and backsheet are products widely used in conventional modules: the encapsulant used in this study is an ultra-fast cure commercial EVA (ethylene vinyl acetate) and the backsheet is a black colored PPE (polyester-polyester-EVA). The reinforcement grid is made of Polyester and HMPE (High Modulus Polyethylene) fibers embedded between two layers of polyester taffeta. A picture of this material is shown in figure 1.

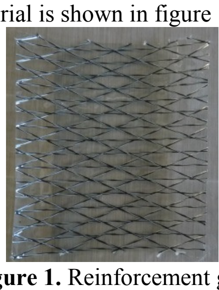

Figure 1. Reinforcement grid

Regarding EVA, the curing process guidelines provided by manufacturers are generally specified for typical PV modules with glass as front cover and no information is available for other concept designs, so recommended curing times and temperatures must be reconsidered. Different sets of samples have been produced varying temperature and time in the lamination process. Polycarbonate sheets of two different thicknesses, namely 2 mm and 4 mm, have been used and lamination parameters have been specifically fixed for each material.

Three diagnosis tests are conducted to evaluate the quality of the samples obtained by changing lamination parameters (temperature and time):

a) Visual appearance: A detailed visual inspection is carried out to detect the presence of visual defects detectable by naked eye as bubbles, wrinkles, delaminations, cracks and any other conspicuous condition.
b) Peel-off test: The procedure followed to measure the adhesive interlayer force is based on standard ISO 813 which determines the adhesive strength between polymeric materials bonded on a rigid substrate.
Sample preparation includes pre-cutting a strip of 10 mm width and at least 100 mm length with a release sheet inserted into the bonded interface to be analyzed. The moving grip of the peel-off machine is fixed to the release sheet and the pull force is applied at a moving rate of (50 ± 5) mm/min making an angle of 90º with the surface.
c) Degree of cure of EVA: Differential Scanning Calorimetry (DSC) technique is used to characterize the degree of crosslinking within EVA encapsulant. The residual enthalpy method, described in future standard as IEC 62788-1-6 Ed.1 currently in draft version, has been used as guidance. According to this method the exothermic peak (around 130 °C to 160 ºC in our fast cure EVA) is due to the heat release from crosslinking reaction in EVA and the area below the curve relates to the percentage of un-crosslinked EVA. Therefore, the gel fraction of crosslinked EVA can be estimated using the following equation:

$$Ge = \frac{hu - ht}{hu} 100$$

Where, *Ge* represents the degree of cure for the enthalpy method (%), *hu* the measured specific enthalpy of EVA of an uncured reference specimen ($J \cdot kg^{-1}$) and *ht* the measured specific enthalpy of EVA of the test specimen ($J \cdot kg^{-1}$). The recommended low and high limits of integration stated in IEC document are 100 ºC and 200 ºC respectively, however the DSC analysis for the uncured EVA employed in this study shows that a (110-190) ºC range matches better with its specific thermal properties.

Although there are not standardized criteria regarding minimum EVA crosslinking degree and peel-off force, it is well accepted by PV industry that EVA gel content above 70% (measured using the primary method) and EVA-glass adhesion strength higher than 60 N/cm are good enough to obtain PV modules suitable for long term operation. The DSC technique used in this work is a secondary method that can be directly applied for quality control when the same EVA formulations are used. In case that DSC results of different encapsulants are to be compared the use of the primary method is recommended. DSC correlation to the gel content primary method can be obtained for encapsulants with curing degrees above 60% so this would be considered as minimum threshold for crosslinking analysis.

2.2. Optical characterization

Polycarbonate samples laminated with EVA have been optically characterized, including the measurement of the spectral transmittance (from 385 nm to 1600 nm) and the yellowness index (YI), which was obtained from it. This optical characterization allowed quantifying the influence of ultraviolet weathering on polycarbonate samples laminated with EVA.

3 RESULTS AND DISCUSSION

3.1 Lamination process

The lamination process has been evaluated in two different steps depending on the number of layers present in each sample. Initially the process is validated for type A laminates which include the PC superstrate, two EVA foils and the backsheet (PPE). Once the laminate fulfills the quality requirements defined through visual, mechanical (peel test) and curing degree (DSC), the rest of the materials (solar cell, extra EVA sheet and reinforcement grid) are included in the package system to obtain the adequate process parameters for the type B multilayer configuration.

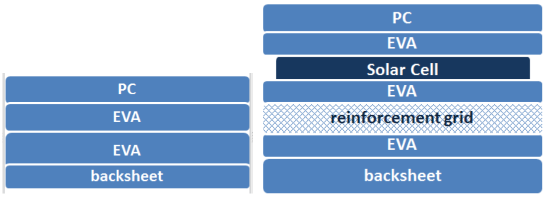

Figure 2: Multilayer architectures used for testing: laminate type A (left side) and type B (right side).

For the purpose of this work, all samples have been manufactured in a (16.5 x16.5) cm size format. The PC sheets studied are 2 mm and 4 mm thick consequently, different processes times and temperatures are used. They are shown in the text table.

Sample Code	Process	Package
16	115 ºC-20.5’	Type A (2mm PC)
15	125 ºC-12.5’	Type A (4mm PC)
17	125 ºC-30’	Type A (4mm PC)

Table I: Process parameters and package description for the first set of laminates

Id.	Inspection	DSC (%)	Peel test (N/cm)	
Code No.	Visual aspect	Cure degree	PC-EVA	PPE-EVA
16	OK	37	84	60
15	OK	44	50	-
17	OK	48	100	65

Table II: Results on first set of laminates evaluated

Analysis of the diagnostic tests conducted over samples 15 to 17 shows that there is not enough crosslinking degree of the encapsulant for the selected process temperatures. Even increasing cycle time, the curing degree of EVA does not increase further. The peel test performed over two interfaces shows that minimum adhesion force of 50 N/cm has been achieved in all cases.

A second set of samples is laminated using higher temperatures for the curing cycle: 135 ºC for samples with 2 mm thick PC sheet and 140 ºC for the 4 mm thickness.

Sample Code	Process	Package
23	135 ºC-12.5’	Type A (2mm PC)
24	135 ºC-17.5’	Type A (2mm PC)
25	135 ºC-22.5’	Type A (2mm PC)
26	140 ºC-12.5’	Type A (4mm PC)

Table III: Process parameters and package description for the second set of laminates

Id.	Inspection	DSC (%)	Peel test (N/cm)	
Code No.	Visual aspect	Cure degree	PC-EVA	PPE-EVA
23	OK	60	99	-
24	OK	72	138	-
25	Bubbles	80	112	-
26	OK	69	120	117

Table IV: Results on second set of laminates evaluated

Characterization results from this second round (samples 23 to 26) show that the more suitable lamination processes for each package system are 135 ºC and 17.5 minutes for the sample with 2 mm thick PC sheet and 140ºC during 12.5 minutes for the one with the 4mm thick PC sheet. For these two recipes the DSC results meet the acceptance criteria stablished and the adhesion force PC-EVA is above the minimum required for glass-EVA interfaces. A maximum curing degree of 80% is reached for sample 25 but visual defects appear in the encapsulant. The adhesion force between encapsulant and backsheet has been measured only for one sample and the value is similar to the one obtained for EVA-PC.

Later on, these processes are reproduced for type B laminates including the rest of material layers and components in each package: solar cells, extra EVA sheet and reinforcement grid. The characterization of the samples is restricted, in this case, to visual inspection and DSC analysis of the EVA foil extracted between the reinforcement grid and the backsheet.

Sample Code	Process	Package
37	135 ºC-17.5’	Type B (2mm PC)
38	140 ºC-12.5’	Type B (4mm PC)

Table V: Process parameters and package description for the third set of laminates

Id.	Inspection	DSC (%)
Code No.	Visual aspect	Cure degree
37	Bubbles	68
38	OK	60

Table VI: Results on third set of laminates evaluated

The sample laminated with the 2 mm thick PC sheet does not meet the visual criteria. The presence of bubbles indicates that temperature of the EVA layer bonded to the PC frontsheet is higher than before even though the same lamination process parameter has been used. Value of crosslinking degree attained for the EVA analyzed is however lower than the one measured for the type A sample laminated using the same parameters what evidences the presence of a temperature gradient across the stack during lamination process.

In order to determine the temperature differences among front (hotter) and back (colder) side of the encapsulant, irreversible temperature labels are placed at each interface during lamination. These indicators are valid to establish temperature ratings in 6 ºC steps, the results show that differences among front and back EVA sheets could range from 1 ºC to 5 ºC.

A final tuning recipe is proposed to define proper lamination parameters for each complete package. The curing time is increased to 15 minutes for the sample with 4 mm thick PC to obtain higher crosslinking degree in the cold side of the sample. In the case of the package with 2 mm thick frontsheet, the curing temperature is lowered to 131 ºC and both configurations (type A and type B) are constructed to perform all diagnosis tests over them.

Sample Code	Process	Package
44	140 ºC-15’	Type B (4mm PC)
45	131 ºC-17.5’	Type A (2mm PC)
46	131 ºC-17.5’	Type B (2mm PC)

Table VII: Process parameters and package description for the fourth set of laminates

Id.	Inspection	DSC (%)	Peel test (N/cm)	
Code No.	Visual aspect	Cure degree	PC-EVA	PPE-EVA
44	Bubbles	-	-	-
45	OK	58	114	97
46	OK	61	-	-

Table VIII: Results on fourth round of laminates tested

Visual defects appear between PC and solar cell (hotter EVA) in sample 44 so the previous process, at 140ºC and 12.5 minutes, is chosen as the best one. No DSC analysis is carried out over this sample.

The results of peel-off test conducted on sample 45 fulfill minimum adhesion strength requirements for PC-EVA (114 N/cm) and PPE-EVA (97 N/cm) interlayers.

The laminate 46 obtained does not present bubbles and the curing degree measured by DSC is 61%.

The picture below shows small bubbles detected around buses of sample 44.

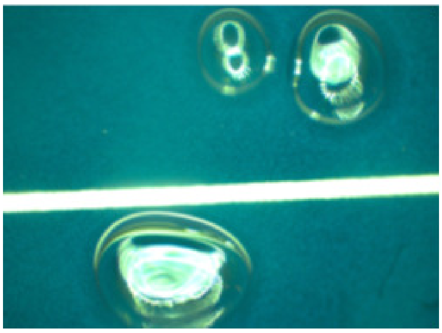

Figure 3: Presence of bubbles in sample 44

Evaluation of type B packages for both PC thicknesses show that maximum degree of cure measured for the EVA bonded to the backsheet (colder side) is around 60%. The attempts to increase this value either using longer lamination times or higher temperatures, cause the bubbles to appear in the hotter side of EVA. In previous laminates experiments the presence of bubbles has been detected for a curing degree around 80%.

In order to estimate the curing degree of the encapsulant adhered to the frontsheet in type B packages where EVA extraction is not possible further analysis are performed.

In the following graph it is presented the curing degree attained for each lamination process used for type A laminates with 2mm thick PC sheet as front cover.

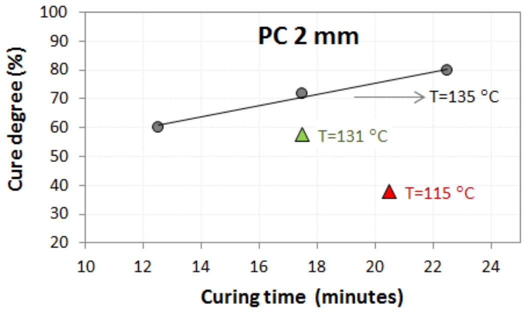

Figure 4: DSC results for different lamination process

Results presented in figure 4 show a linear behavior of curing degree versus lamination time for the same target temperature (135 ºC). For the specific case studied, every 5 minutes step in curing time represents a 10% increment in crosslinking degree determined by DSC. On the other hand, a temperature decrement of 4 ºC for the same lamination time (17.5 minutes) results in a 14% reduction of the curing degree what represents a 3.5% variation per ºC. Taking into account that temperature differences between both EVA sides in type B packages could range from 1ºC up to 5 ºC it is expected curing degrees to vary accordingly.

3.2 Effect of ultraviolet weathering

Polymers often show high sensitivity to ultraviolet light, and as a result they suffer significant degradations when exposed to sunlight. With the aim of investigating durability aspects of outdoor exposure, 3 polycarbonate samples (2mm thick) laminated with EVA using different lamination conditions have received a total ultraviolet irradiation of 28 kWh/m^2 (94% corresponding to UVA and 6% to UVB). Polycarbonate side was placed facing the incident ultraviolet irradiation.

In the following table the lamination conditions for each sample together with the results of the optical characterization before and after the ultraviolet weathering test are shown. The transmittance (T) corresponds to the averaged values between 385nm and 1600nm.

Id.	Lamination		Before		After UV	
			T(%)	YI	T(%)	YI
07	125 ºC	12.5’	86.2	2.50	85.8	3.18
08	120 ºC	20.5’	86.0	2.59	85.9	3.05
09	115 ºC	20.5’	85.8	2.51	85.9	3.09

Table IX: Lamination conditions and optical characterization of polycarbonate samples laminated with EVA before and after UV irradiation

As can be appreciated from the previous table, the initial transmittance shows minor differences among 3 different lamination conditions examined and slight decrease of this parameter is observed after the ultraviolet test. On the other hand, the yellowness index was clearly influenced by the ultraviolet weathering test, increasing its value for the 3 samples. The different lamination conditions did not show relevant influence in the optical characteristics of the 3 samples or in the ultraviolet test effect.

4 CONCLUSIONS

The BIPV module lamination processes for 2mm and 4mm thick polycarbonate (PC) frontsheets proposed in the AiSoVol project have been adjusted and validated.
A fine control of the lamination parameters has been achieved for each specific package so that time and temperature can be individually set in order to obtain specific curing degrees of the encapsulants.
Selected processes for each package system are 131 ºC and 17.5 minutes for the sample with 2 mm thick PC sheet and 140ºC during 12.5 minutes for the one with the 4mm thick PC sheet. The results of the peel test for type A samples laminated with these parameters are 114 N/cm in the PC(2mm)-EVA interlayer and 97 N/cm and 117 N/cm in the EVA-backsheet with 2mm PC as frontsheet. The peel forces measured in the type A sample with 4mm thick PC are 120 N/cm and 117 N/cm for the same interfaces. The degree of cure for the type B laminates is around 60% for both PC thicknesses analysed.

Temperature gradients through the complete package during lamination processes have been measured. Correlation between lamination parameters (time and temperature) and the curing degree for type A laminates with 2mm thick PC sheet has been quantified. An increase of one ºC in lamination temperature implies 3.5% improvement in the curing degree and 5 minutes longer cycles at a fixed temperature represents 10% higher curing rates.With the aim of investigating durability aspects of outdoor exposure, polycarbonate samples laminated with EVA have undergone an ultraviolet weathering test. In this case, 3 polycarbonate samples (2mm thick) laminated with EVA using different lamination conditions have received a total ultraviolet irradiation of 28 kWh/m^2, (94% corresponding to UVA and 6% to UVB). As a result of this test the transmittance showed a slight decrease after the ultraviolet test. On the other hand, the yellowness index was clearly influenced by the ultraviolet weathering test, increasing its average value for the 3 samples. The different lamination conditions applied in this case did not show relevant influence in the optical characteristics of the 3 samples or in the ultraviolet test effect.

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