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The Impact of the Lamination Process on the Adhesion Properties at the Glass-Encapsulant Interface and Damp Heat Stability of PV Modules

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ABSTRACT: This paper presents an extensive study of the influences of the lamination process on the adhesion properties of the glass-encapsulant interface of different laminates. The investigations were conducted on small-scale laminates which were laminated with different material combinations at peak lamination temperatures from 140°C to 180°C. As a measure of the long-term durability, the laminates were exposed to damp heat (DH) up to 3000 hours. We investigated the development of the adhesion between encapsulant and glass by peel tests, the measurement of the gel content and the colour change of the backsheet by measurements of the yellowness index. The peel test results show that the relative maintained peel force (RMPF) varies in the range from 15.7-73.0% depending on the material and the lamination process. It is obtained that the EVA laminates showed less degradation in peel force after DH than POE samples and a higher lamination temperature was beneficial in peel force and gel content before and after ageing for cross-linking encapsulants such as EVA and POE. For the used TPO the peel force did not change for different lamination temperatures. We showed that with lamination temperatures up to 180 °C EVA, POE and TPO modules can be manufactured and withstand DH ageing but they may show a slightly increased yellowing of the rear side.

Keywords: PV modules, peel test, damp heat, backsheet, degradation

1.INTRODUCTION

A current topic in the Photovoltaic (PV) module industry is the process time reduction to achieve higher throughput for module manufacturing [1]. However, these modules also need to operate for long lifetimes of more than 25 or even 30 years [1,2]. A good adhesion between the module layers may prevent delamination, which is a defect that occurs in the field and repeatedly leads to lifetime issues [3]. Another frequently observed indication of PV module ageing is the yellowing of the materials [5].

The adhesion strength at the different interlayers of the laminate and the yellowing after ageing are influenced by the choice and interaction of the encapsulant materials and the process parameters during lamination. Therefore, to ensure good adhesion, it is essential to choose the lamination parameters and materials carefully [6]. Module manufacturers aim to increase their lamination temperatures from 150°C to higher temperatures [7]. The goal is to speed up the lamination process and realize a higher throughput of module production. But so far, there are not many studies about the influences of high lamination temperatures on the long-term adhesion properties of the material compound in the module.

Damp heat ageing is a common way to accelerate the ageing of PV modules by driving humidity into the module package which leads to a decrease in adhesion strength of the interfaces [8,9]. To evaluate the stability of the multilayer composite of a PV-module, peel tests after damp heat (DH) tests with long durations can be conducted.

This paper investigates long-term effects of lamination temperatures > 150°C in terms of peel force measurements and evaluation of the discolouration in terms of the yellowness index before and after DH 1500 and DH 3000 exposure. Additionally, the different failure types that occurred during the peel tests and the gel contents of the EVA encapsulant were analysed in detail.

2.MATERIAL AND METHODS

2.1 Sample Preparation

Small scale laminates (200 mm x 200 mm) with polypropylene (PP) and polyethylene terephthalate (PET) based backsheets were laminated with ethylene-co-vinyl acetate (EVA), polyolefin elastomer (POE), and thermoplastic polyolefin (TPO) based encapsulants at peak laminations temperatures of 140 °C, 160 °C, and 180 °C. The lamination time varied between 4-10 minutes as shown in Table 1.

Table 1: Parameters of the Lamination Process

Temperature [°C]	Curing time [min.]
140	10
160	10
180	4

The specifications and properties of the different encapsulation materials that were used in this study are shown in Table 2. The material combinations represent common, commercially available products from the PV market.

2.2 Damp Heat Test

The influences of the lamination process on the adhesion properties under water vapour ingress were investigated by exposing the modules to the damp heat test (85 *°C*, 85 % r.*h.*) for 1500 h and 3000 h. The modules were characterized before and after the DH-test regarding their peel force, gel content and yellowness index.

2.3 Peel Tests

The peel force at the glass-encapsulant interface is measured with the PSE peel-off instrument at an angle of 90° (Figure 1). The peel tests were conducted at the centre of the small-scale laminates according to the BS EN ISO 8510 standards [9] by cutting strips with the width of 10 mm and length of 200 mm[10]. These strips were peeled off with a speed of 50 mm/min at room temperature. The relative maintained peel force (RMPF) of the laminates after been exposed to the DH 3000 test is calculated with the formula:

$$RMPF = \frac{Peel\ force\ after\ DH\ 3000}{Initial\ peel\ force}\ x\ 100\%$$

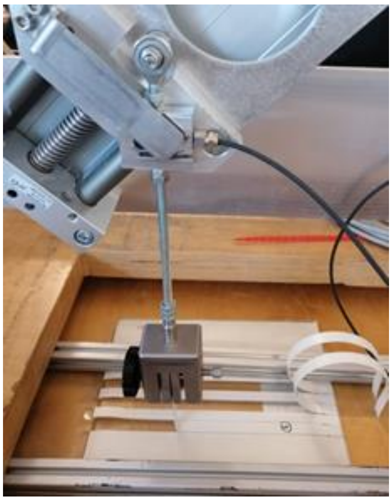


Figure 1: 90° Peel test at the glass-encapsulant interface

2.4 Gel Content Measurements

To investigate the correlation of the peel force at the glass encapsulant interface and gel content of the encapsulant, the Soxhlet extraction method was used to measure the gel content. In this method, small pieces of the encapsulant, extracted from the laminate samples are dipped into a solvent for a certain period [11]. The solvent and the period changes according to the type of encapsulant that is measured. The gel content was calculated with the following formula [2];

$$Gel\ content\ (\%) = \frac{M_2}{M_1}\ x\ 100$$

where M_1 represents the initial weight of the specimen and M_2 its weight after the extraction and drying process.

2.5 Colour Measurements

The degradation of encapsulants in laminates can also be investigated by using colour measurements. The tests, on both sides of the laminate, were performed according to the EN ISE 11664-4 standards by characterising the laminates with respect to their yellowness index (YI) [12]. To do this, a portable ColorLite sph900 spectrophotometer with an observer angle of 10° was used.

Table 2: Specifications and properties of the encapsulation materials used in this work

Layer	Material	Thickness [mm]	Water Vapour Transmission Rate [at 38 °C, 90 % r.h.]
front glass	safety glass	3	0
encapsulant	EVA	0.5	n.a
encapsulant	POE	0.5	n.a
encapsulant	TPO	0.4	n.a
backsheet	PET/PET/Primer	0.295	2.4
backsheet	PET/Aluminium/PET/Olefin	0.33	n.a
backsheet	PP	0.36	0.6

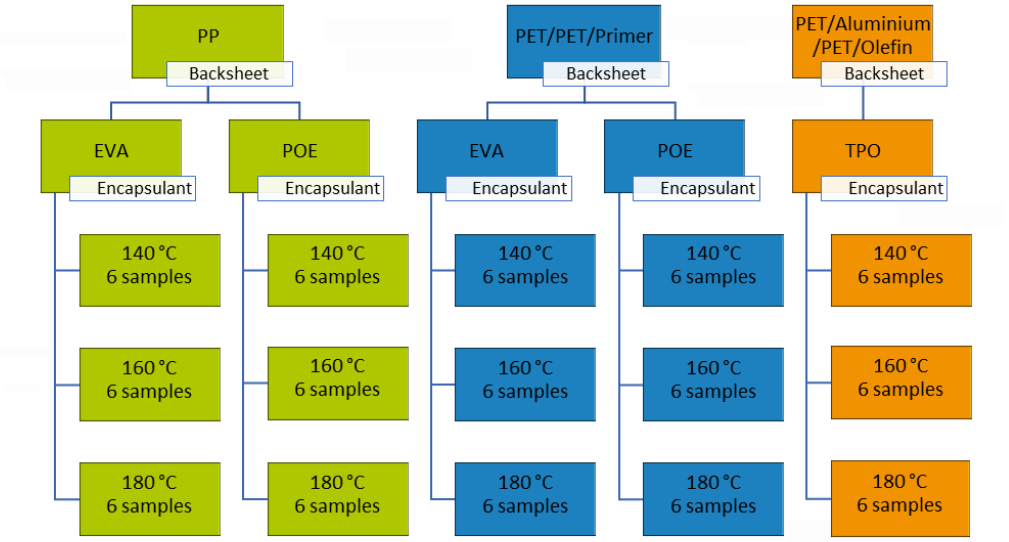


Figure 2: Material combinations and number of laminates built for the study

3.RESULTS

In this section, the different lamination processes are evaluated according to the gel content and peel tests and considering the influences of the water vapour ingress after DH characterised according to the trend in gel content, peel force and yellowness index.

3.1 Gel Content

The change in gel content of the EVA based laminates according to their peak lamination temperature and lamination time is analyzed directly after lamination and after 1500 and 3000 h DH.

For each experimental point, two laminates were used, and measurements were taken from two random locations of these laminates. Each measurement point shown in Figure 3, corresponds to the average value of these four measurements with the error bars indicating the standard deviation.

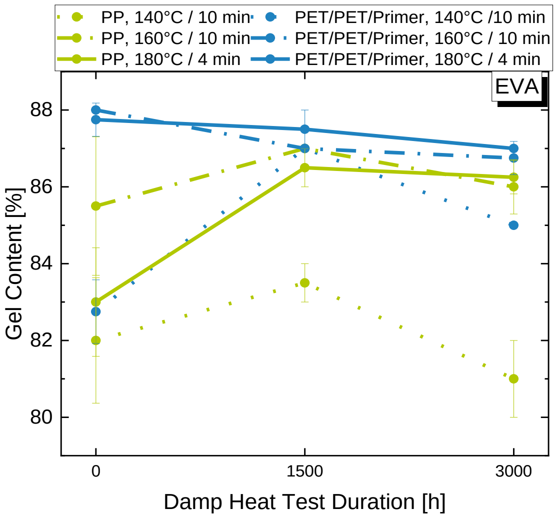


Figure 3: Gel-content of the EVA laminates with PP or with PET backsheet directly after lamination, after 1500 h and 3000 h damp heat test.

For the un-aged laminates, it was found that the gel content of the 160 °C laminates was slightly higher than the ones laminated at 180 °C. This happened due to the lower lamination time at 180 °C. The 160 °C laminates had a curing time of 10 minutes, while the 180 °C laminates had a curing time of 4 minutes.

After being exposed to DH 1500, the laminates with the PP backsheet showed an increased gel content, while the laminates with the PET backsheet show a slight decrease in gel content. Exposing further with DH 3000, the gel content of all samples decreased slightly.

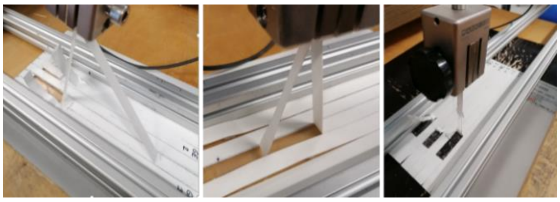
As reason for this behaviour, we suspect that the exposure to an elevated temperature during the DH-test may lead to a post-crosslinking in the encapsulation material. Another effect is a degradation of the material due to the humid environment which slowly leads to a decrease in gel content. For samples with initially comparable low gel content the post-crosslinking dominates while further exposing to humidity or with a high gel content from the start the degradation effect due to humidity dominates.

Overall, all samples show an acceptable gel content before and after each DH step.

3.2 Peel Test Failure Type Analysis

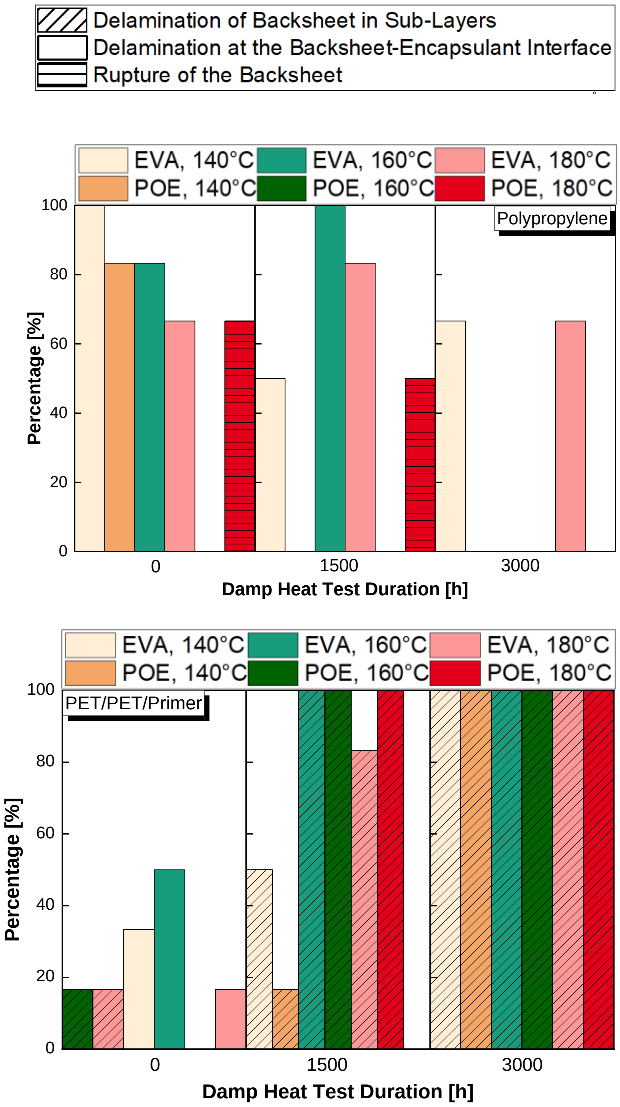
In this section and the next section peel forces at the glass encapsulant interface before and after DH for the different lamination temperatures and lamination setups are analyzed. Firstly, an investigation of the different failure modes is performed and in the second part the peel force is investigated.

Each peel force measurement was done on two laminates with each three peel tests, respectively. This section analyses the type and number of failures that were observed during the peel tests in correlation to the used materials and the peak lamination temperature of the laminates. Some of the laminates showed multiple types of failures, and in that case, the failure type that occurred first was taken into consideration. We observed three failure types: a) delamination of backsheet in sub-layers, b) delamination at the backsheet-encapsulant interface and c) rupture of the backsheet. Representative examples are shown in Figure 4.



(a) (b) (c)

Figure 4: Photograph of the back sheet failure mode occurred during the peel test: Delamination of Backsheet in Sub-Layers (a), Delamination at the backsheet-encapsulant interface (b), and rupture of the Backsheet (c)



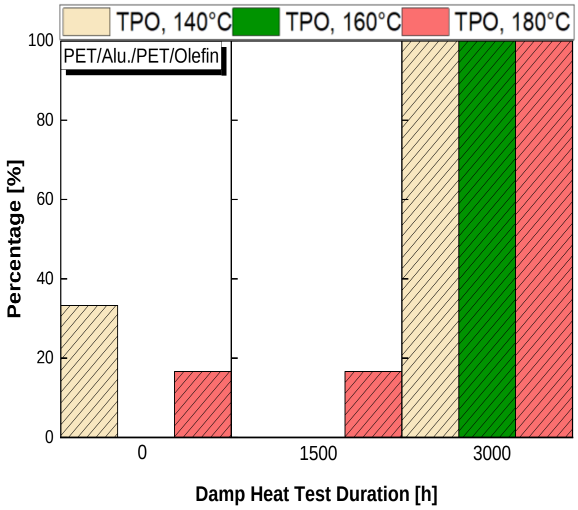


Figure 5: Failure type distribution of the different material combinations

Figure 5, shows the different failure modes depending on the materials and the degradation times [13].

For the samples with PET/Aluminium/PET/Olefin backsheet, the only failure mode was delamination of backsheet in sub-layers. These occurred for 40.7 % of the samples and indicates a potential issue of the backsheet itself under long DH exposure. A similar trend was observed for the laminates with the PET/PET/Primer backsheet. Here, the major failure type before ageing was delamination at the backsheet-encapsulant interface, while it changed to delamination of the back sheet in sub-layers after damp heat exposure. Again, it suggests an issue of the backsheet under long DH exposure.

For PP backsheets the most observed failure was a delamination at the the backsheet-encapsulant interface however for high DH exposure the encapsulant-glass interface could be measured. A rupture of the backsheet was observed in cases for POE encapsulant with an overall high peel force (see next section).

3.3 Peel Test

Each measurement point in this section corresponds to the average peel force of the six peel tests. The standard deviation is indicated with the error bars. Depending on the failure mode (shown in the previous section), the sample size for individual measurements points may be smaller, since only the peel force of the glass- encapsulant interface is evaluated here. , shows the measured peel-force over the lamination peak temperature before DH-test. The colours represent the different backsheets, PET/Aluminium/PET/Olefin in orange, PET/PET/Primer in blue and PP in green, while the symbols show the used encapsulant.

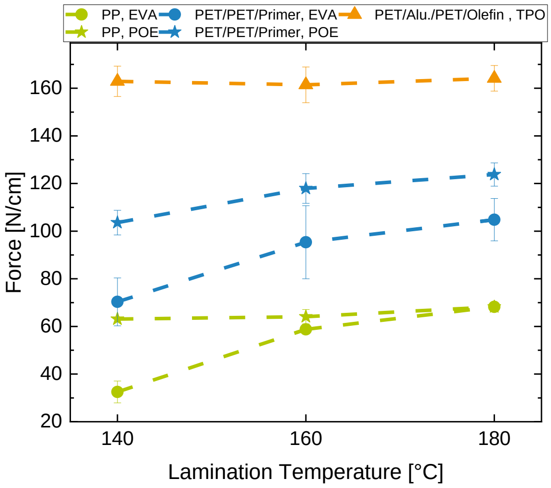
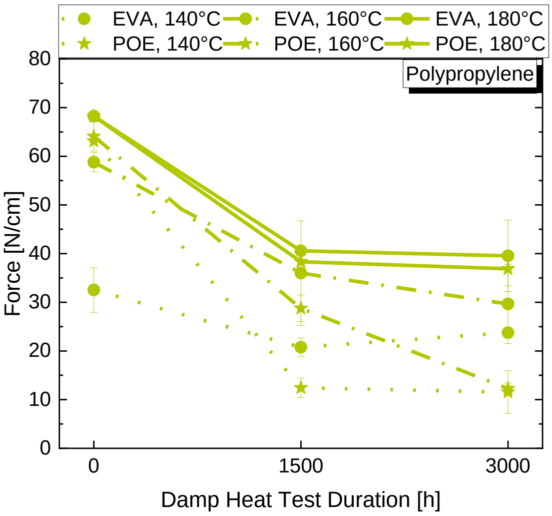
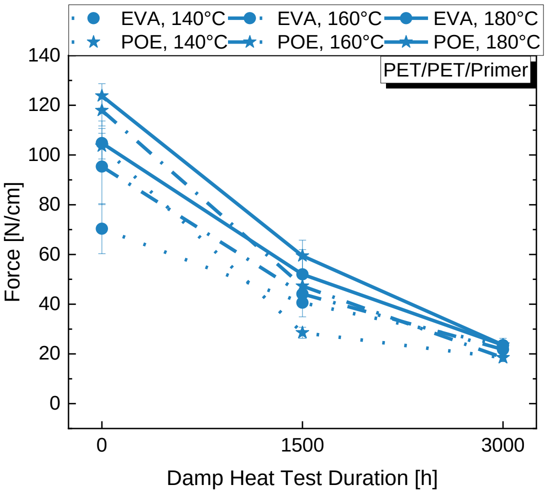


Figure 6: Initial peel forces obtained from the glass-encapsulant interface

The laminates with the TPO encapsulant have a consistent peel force of around 160 N/cm independent from the peak lamination temperature. The reason is that TPO does not require any cross-linking it just needs to exceed its melting point during lamination to form a good contact. EVA and POE require a certain time-temperature budget for the cross-linking reaction; therefore, we observe differences for the different lamination temperatures [2,14]. The peel forces for lamination temperatures of 180 °C are the highest even with shorter lamination times. For the PP backsheet, the peel forces are consistently lower than for the PET backsheet since it does not facilitate a primer layer. However, it is already a strong indication that the lamination setup was not sufficient for this parameter setup. This sample also showed the lowest gel content as seen in Figure 3.

The influence of the damp heat stability on the peel force for the different material combinations is presented in Figure 7 while the RMPFs calculated from these graphs are shown in Table 3.





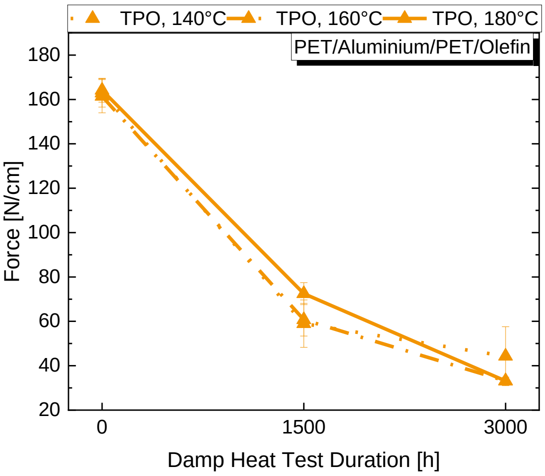


Figure 7: Peel force at the glass-encapsulant interface after 1500 h and 3000 h DH for the laminates with polypropylene, PET/PET/Primer, and PET/Aluminium/PET/Olefin backsheets respectively.

The graphs show that the highest peel force degradation occurred at the laminates which used the PET/Aluminium/PET/Olefin backsheet with a TPO encapsulant. While these laminates had peel forces of around 160 N/cm before the damp heat exposure, they dropped to 33-45 N/cm after exposing them to DH for 3000 hours. However, the absolute values of peel force are still amongst the highest overall and at DH 3000 all samples failed because of a delamination within the backsheet.

A strong drop in peel force is also observed for the laminates with the PET/PET/Primer backsheet. These laminates dropped from around 120 N/cm to 18-25 N/cm after DH 3000.

The laminates with polypropylene backsheet on the other hand had much lower peel forces (~65 N/cm) before DH testing compared to the other two backsheets, but after the damp heat exposure they degraded less than the others and their peel forces dropped to ~30 N/cm. At most of the polypropylene laminates, it is observed that the degradation rate lowered a lot by becoming around 15 % or even less, after DH 1500.

Comparing the results to the gel content measurements in Figure 3 it can be deduced that the samples with low gel content (before ageing) also expose a lower peel force. After ageing the peel force is reduced for all sample but still a lower gel content also means a lower peel force. This correlation between peel force and gel content is expected, since a more cross-linked material should show a stronger adhesion force. However, a quantification was not possible in this work.

Comparing the results to the moisture ingress as it can be seen in Table 2, that the PP backsheet has a comparably low WVTR [6,15]. Therefore, a lower degradation is expected. The decrease in peel force of the PET/Aluminium/PET/Olefin laminates on the other hand is not yet fully understood, because it is expected that the aluminium layer functions as a moisture barrier. However, since delamination of the backsheet in sub-layers occurred in all cases after DH 3000, further investigations should consider whether the backsheet is inherently degraded.

Comparing the different lamination conditions, it is observed that independent of the material combination, a low initial peel force is also followed by a low peel force after DH 1500 or DH 3000. Therefore, a higher process temperature is beneficial for higher peel forces initially and after DH exposure.

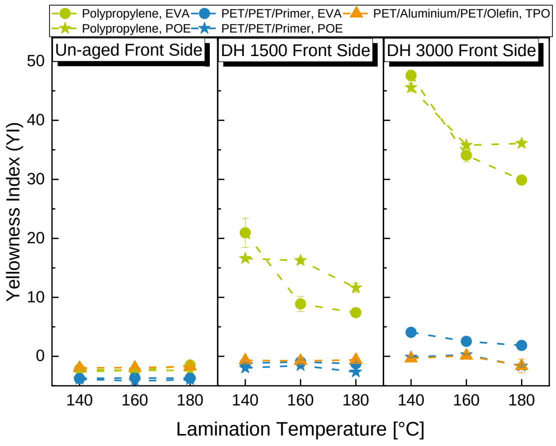
It is also observed, that independent of the lamination conditions, POE has a lower RMPF and therefore shows a higher degradation rate than EVA, which indicates that POE may be more susceptible to degradation by water vapor in terms of peel force.

Table 3: List of the used materials and the related average peel force values before ageing, after DH 3000 and the relative change of the peel force

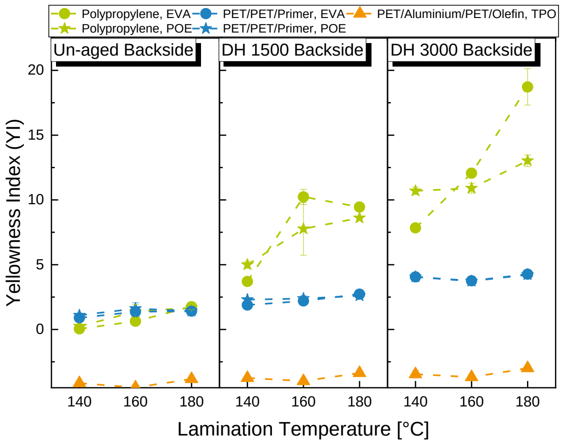
Backsheet	Encapsulant	Lamination Temperature [°C]	Initial Peel Force [N/cm]	Peel Force after DH 3000 [N/cm]	Relative Maintained Peel Force [%]
polypropylene	EVA	180	68.23	36.88	54.1
PET/PET/Primer	EVA	180	104.81	23.54	22.4
polypropylene	EVA	160	58.80	29.66	50.4
PET/PET/Primer	EVA	160	95.36	21.80	22.9
polypropylene	EVA	140	32. 52	23.75	**73.0**
PET/PET/Primer	EVA	140	70.33	23.43	33.3
polypropylene	POE	180	68.23	37.24	54.6
PET/PET/Primer	POE	180	123.78	23.62	19.1
polypropylene	POE	160	64.09	12.27	19.2
PET/PET/Primer	POE	160	117.93	18.48	15.7
polypropylene	POE	140	63.12	11.55	18.3
PET/PET/Primer	POE	140	103.59	18.53	17.9
PET/Aluminium/PET/Olefin	TPO	180	**164.17**	33.12	20.2
PET/Aluminium/PET/Olefin	TPO	160	161.44	33.12	20.5
PET/Aluminium/PET/Olefin	TPO	140	162.91	**44.29**	27.2

3.4 Colour Measurements

To study the optical degradation, colour measurements were conducted. The results were evaluated at the front side and the rear side of the laminates and are shown in Figure 8.



(a)



(b)

Figure 8: Yellowness index of the laminates with different material combinations (blue, green, orange) at different peak lamination temperatures on the (a) front side and (b) rear side of the laminate after lamination (left), after DH 1500 (middle), and after DH 3000

Before ageing the YI is quite similar for all lamination conditions when measured from the front side. After DH exposure (DH 1500 and DH 3000) the 180°C laminates, show on the front side a lower YI in contrast to the 140°C laminates for the PP backsheet and for a slightly lesser degree for the other backsheets. However, when considering measurements on the rear side, the YI of the backsheets increases for higher lamination temperatures after ageing. A possible interpretation is that the backsheet is yellowing because of chemical reactions within the backsheet and within the encapsulant. At the rear, the process within the backsheet is dominating and an initial "burning" of the backsheet for higher lamination temperatures may increase during ageing.

For the front side the dominating factor might be the amount of the uncross-linked encapsulants. The polypropylene laminates had already a lower degree of cross-linking to begin, and the material might be more sensitive to chemical reactions caused by this uncross-linked particles. However, with a higher crosslinking degree (linked to higher lamination temperatures) these effects may be reduced.

Overall, PP backsheet shows the highest YI after degradation. The melting point of PP is much lower compared to the other backsheets that are used in this study. This might have caused chemical changes in the backsheet material during the lamination process which in turn led to the high YI values.

4. CONCLUSION

An extensive study to gain a deeper understanding of the influences of the lamination conditions and the DH stability of small-scale laminates featuring different backsheets and encapsulation materials was conducted. We used three different peak lamination temperatures (140°C, 160°C, and 180°C) with different curing times, and exposed the laminates to DH for 1500h and 3000 h.

The results indicated that laminates with POE and the EVA encapsulant show higher peel forces when laminated at higher temperatures, while the TPO-based laminates showed consistent peel forces independent of the peak lamination temperature. This also generally applies for the peel force after DH exposure. POE samples showed overall a higher peel force initially, while EVA did generally degrade less than POE during DH exposure. The degradation rate with PET based backsheets was higher than with the PP backsheets but the peel force after ageing was still higher than with PP backsheets. The results also show a correlation between the gel content and the measured peel forces. Laminates with a low degree of cross linking had a low peel force. Our interpretation would be that the peel force is increasing parallel with higher gel contents until a certain degree of cross linking where the influence of the gel content becomes negligible. The results of the failure type analysis indicate that the failure type that occurred during the peel test is mainly affected by the backsheet structure. The PP backsheet was the only one at which rupture of backsheet occurred while both PET based backsheets showed delamination of the backsheet in sub-layers after the DH 3000 for all test samples.

The colour measurements showed an increase in yellowing index from the rear side for increased lamination temperature but a decrease in yellowing index from the front side, which may hint to different yellowing reactions inside and outside of the module.

Overall, it can be concluded that module laminated with elevated temperatures of up to 180 °C can be manufactured and they withstand DH3000 tests in terms of peel force and yellowing. This may allow for faster lamination processes.

5. ACKNOWLEDGEMENT

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