INTEGRATION OF FLEXIBLE SOLAR CELLS IN PLASTIC AND COMPOSITE MATERIALS

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ABSTRACT: Processes have been developed to integrate CIGS solar foils directly in plastic or composite based products. Using injection moulding and vacuum forming it turned out that mechanical stress is applied to the solar foil upon cooling. Using intermediate stress relief layers such as polyolefin this could be reduced considerably. The high temperatures needed in injection moulding have only a minimal effect on the performance of the solar cells. Making curved products is possible with the solar foils, leading to new markets for solar energy. Outdoor performance is attractive, but indoors only applications that require little power are feasible.
Keywords: Flexible Substrate, CIGS, Product Integration

1 INTRODUCTION

Application of solar energy is focused on large-scale applications to battle climate change and reduce greenhouse emissions. Forgotten is often the use of solar energy to power small autonomous devices. The value of the energy is much higher than bulk electricity. Therefore, it is worthwhile to look at the integration, physically and electrically, in appliances ranging from lighting to roof tiles and from sensors to road infrastructure. Producers of these products are interested in the energy harvesting, aesthetically nice integration while maintaining the conditions of their processes.

This paper focuses at the physical integration of thin-film flexible solar foils to be able to make curved products. New processes are developed to integrate flexible solar cells into plastic and composite materials based on well-established techniques as injection moulding, vacuum forming and vacuum bagging. This creates a broad range of design and application possibilities. Using solar foils it is possible to make PIPV (Product Integrated Photovoltaics) products that need not to be flat. This creates new opportunities for PV and opens markets where crystalline silicon cannot be used.

As seamless integration of flexible solar cells in the production process is aimed for, harsh production conditions such as high temperature and high pressure must be dealt with. Knowledge about the productions processes of plastics and composites must be connected with the expertise on thin-film flexible CIGS. In this research an important aspect is the adhesion of the cell to the plastic or composite material.

2 INTEGRATION TECHNIQUES

The industrial partners in the SEPAC project[1] are producers of plastic and composite based products that are highly interested in the possibilities to use solar energy to partially power their products. Commonly the solar modules are attached to the products in the final stage. From a process point of view and aesthetically it is favoured to apply the solar cells in the production process. This can be done with solar foils, as the can form to the product shape. The research question is to what extent the temperature and mechanical stress can be dealt with by the solar cells and whether good adhesion can be achieved.

2.1 Injection moulding

Most plastic products are manufactured with injection moulding. Plastic pellets are dried and then fed through a hopper in a heated chamber where they melt. With a hot screw-type plunger the molten plastic is under high pressure pressed in a heated mould. After solidifying the mould is opened and the product removed. The moulds are very expensive and the time to prepare the pellets considerable, so, it is mostly used for large series.

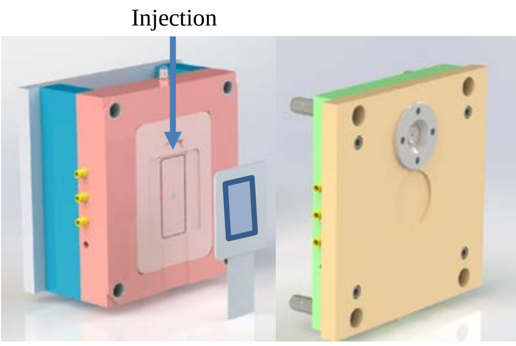

Figure 1 Mould used for testing solar foils

In Figure 1 can be seen that thin plates are made with the solar foil underneath. Injection parallel to the solar foil is favoured to minimize the force exerted on the solar cell and gives a uniform plastic sample. This set-up is used to test the adhesion of the foil to the plastic.

2.2 Vacuum forming

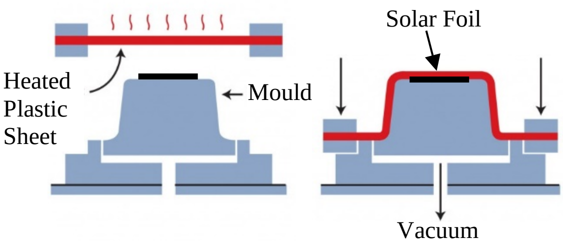

Figure 2 Vacuum Forming

In Figure 2 can be seen that a thermoplastic sheet gets hot using IR heaters. It softens and is stretched over a mould. In this work a solar foil is laid on a warm mould and pressed into the plastic sheet.

2.3 Composites

For structural materials, resins reinforced with fibers are used. The commonly used resins are polyester, epoxy or vinyl ester. Fibres woven to give directional strength can be transparent, glass-based, allowing to be on the sunny-side of the solar cells or non-transparent such as carbon or aramid.

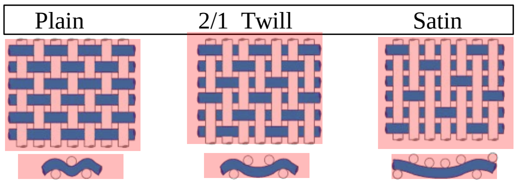

Figure 3 Fibres different weave patterns resin filled (red)

3 SOLAR FOILS

In this study CIGS flexible ICI solar modules are used from Global Solar[2]. Six cells of 220 mm are connected in series via 5 dots to result in 3.3 V module. They can be cut in rectangular shapes to fit with the required product. This will lower the current and/or the voltage.

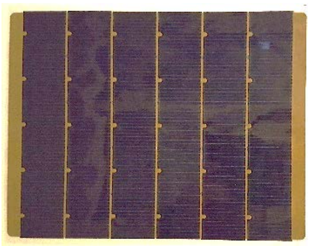

Figure 4 CIGS ICI module horizontal cut lowers the current Vertical cut for a discrete number of cells

The modules, as received, encapsulated in thin PET foil have a limited lifetime. Depending on the application the encapsulation must be adapted. For outdoor use it is needed to laminate the modules with polyolefin and a 125 µm barrier PET foil to prevent moisture ingress.

3.1 Mechanical stress

During processing considerable forces can act on the solar foils. Therefore, tensile testing is performed to get an impression to what extend a module can be stressed and where the weak points are.

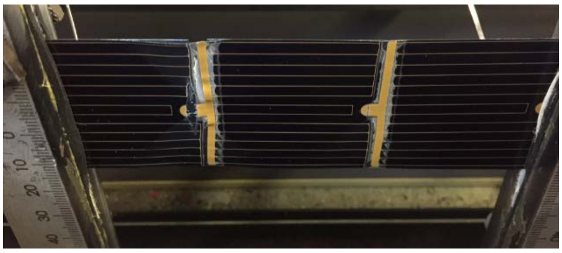

Figure 5 Solar Foil in Tensile Testing Machine

In Figure 5 can be seen that the contact area where the cells are series connected is deformed, left, and delamination takes place, right contact. In Figure 6 can be seen that eventually the whole cell is delaminated.

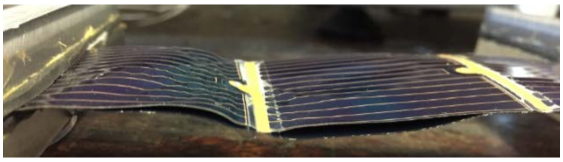

Figure 6 Delamination upon stretching

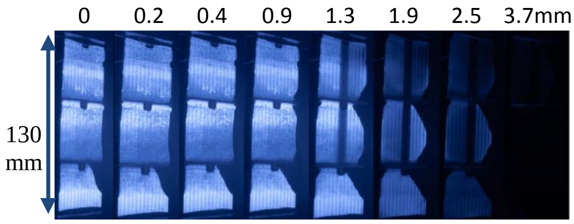

Figure 7 EL picture of a stressed solar foil

In Figure 7 can be seen that with an elongation of 1% (1.3 mm) the cell interconnects fail.

3.2 Thermal stress

ICI submodules should not be processed above 160°C[2]. Higher temperatures might be applied but only for a limited time. In chapter 4 will be shown that in injection moulding the solar foils can withstand process temperatures up to 250°C, though with a decreased efficiency.

3.3 Energy Yield

The first question to be answered is how much energy is harvested in order to establish the storage capacity needed. There is a great distinction between outdoor and indoor use.

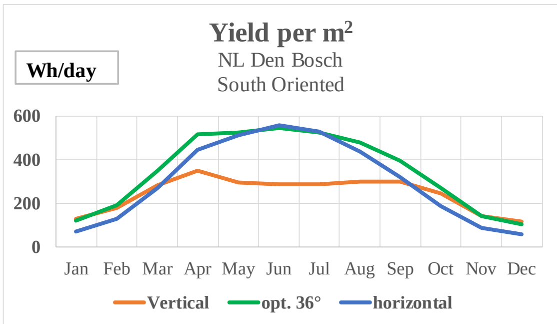

Figure 8 Energy yield of 1 m2 ICI Modules in NL

The outdoor yield is calculated using PVGIS[3] for a 122 Wp system and a PR of 85%. At maximum an average of 500 Wh/day can be harvested.

Indoor the light intensity is limited. In an office the light intensity is typically 500 Lux ≈ 5 W/m^2. The PV power is then 0.6 W/m^2, assuming an efficiency of 12%. For the present generation CIGS this is far too optimistic [4]. In 8 hours the energy yield is 5 Wh. The battery of a Samsung S8 12 Wh. So, in the best case 1 m^2 of CIGS can only power a smart cell phone for 50%. In case of a window, day light, energy harvesting becomes far better.

4 INJECTION MOULDING

As a first step the adhesion of the several foil to the injected plastic is studied. For 4 materials a plasma treatment, Surface Dielectric Barrier Discharge (SDSB) with N2, was used.

Table 1 Adhesion of foils on injected plastic

Mass \ Foil	PC	PP	PO	PFA	PFA plasma	ETFE	ETFE plasma	PET	PET plasma	PEN	PEN plasma
PC											
PP											
ASA											
PBT											
PBT-PC											
PET											
Tritan											
PS											
ABS											

No adhesion
Limited (≈ 3 MPa), not reproducible adhesion
Strong adhesion (> 7 MPa)

In Table 1 can be seen that only the combination of the foils polypropylene and polycarbonate with their own injected plastic give a proper adhesion as tested according to ASTM D4541 with a Dolly. For PC and PP the glue to mount the dolly was the weak point, not the PC-PC or the PP-PP interface

This result means that adhesion on the solar foil, with PET as outer surface, needs a new approach. As can be seen in Table 1 PP-PP and PC-PC are promising combinations. So, when laminating the solar foils first PO, then an additional layer of polycarbonate, 125µm (Lexan 8010 of Sabic), was added or polypropylene, 25µm (Innovia Propafilm RGP) or 300µm (Priplak Opaline).

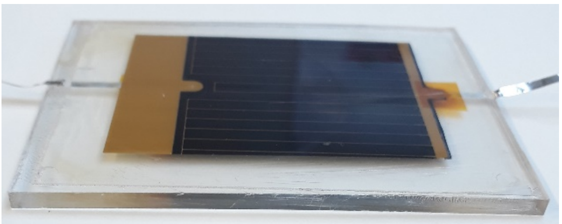

Figure 9 Solar Foil with PC foil 125 µm on injected PC

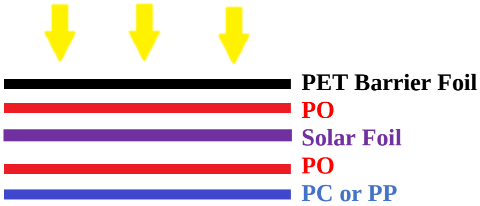

Figure 10 Lay-up for sample shown in fig.9 and fig.11

It can be seen in Figure 9 that a flat sample is obtained. No detachment is observed after 800 hours Damp Heat. The sample can be placed under or above the polycarbonate as the layers are transparent. In this simple structure it is assumed that the thick injected PP or PC layer protects the solar foil from water ingress.

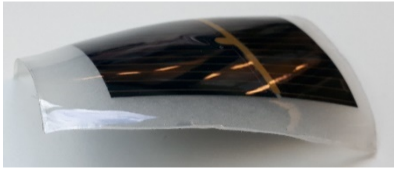

Figure 11 Solar Foil with PP foil 300 µm

The process applied for polycarbonate doesn't work for polypropylene as can be seen in Figure 11. The shrinkage of PP results in a bent sample, as the PET-encapsulated solar foil doesn't shrink with temperature. Such a curved sample cannot be put in the mould; Figure 1. So, a symmetric lay-up is made, as shown in Figure 12.

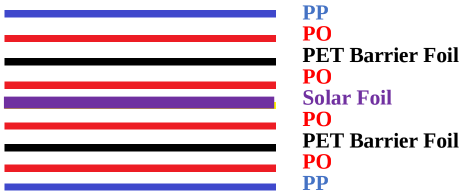

Figure 12 Symmetric lay-up

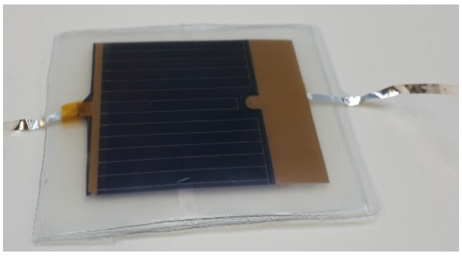

Figure 13 Solar Foil on PP with a symmetric lay-up

In a symmetric lay-up the bending of the PP-sample is prevented. This allows to sample to be put in the mould. However, the difference in thermal expansion between the inject PP and the PET foil still gives bending as can be seen in Figure 14.

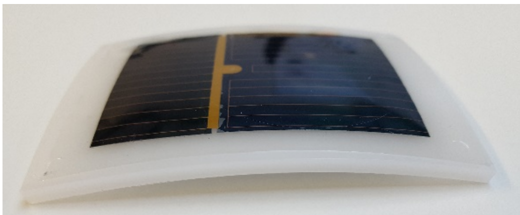

Figure 14 Solar Foil with PP foil 25 µm on injected PP

The pressures in the injection moulding process where 160 bar and temperatures up to 250°C. In Figure 15 can be seen that after injection moulding the cell efficiency drops significantly. For 200°C the cell performance restores to a large extent. It was tested whether light soaking[5] might restore the cells. Light soaking for 20 hours, indeed restores the cell performance to a large extent. However, 64 hours of soaking, influenced the cell efficiency negatively. With a proper light soaking even temperatures up to 250°C can be used for injection moulding. It should be realised that the cells will not reach 250°C, because the mould is at a lower temperature. In addition, the total process time is only tenths of seconds.

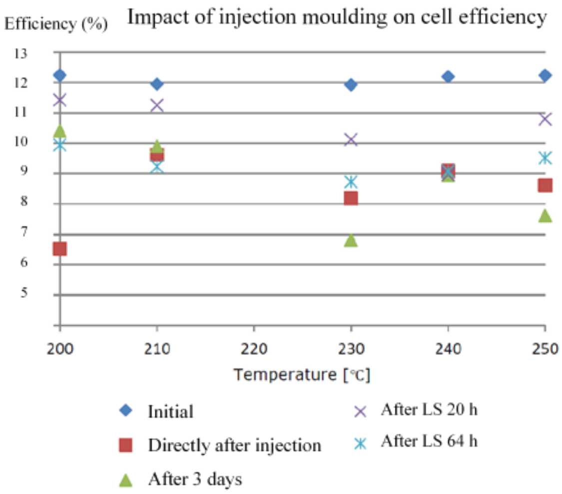

Figure 15 Impact of injection moulding temperature on cell efficiency

5 VACUUM FORMING

The challenge when integrating solar foils in vacuum formed plastic products is handling the shrinkage of the plastic. In this work PETG and ABS are used. Both show similar behaviour, so only PETG is described in this paper.

PETG is heated to 130-140°C, and is very soft then can easily be stretched. After removal of the IR-heaters vacuum is applied and the PETG is stretched over the mould. After cooling down to 80°C, the plate with mould is taken out and the mould removed.

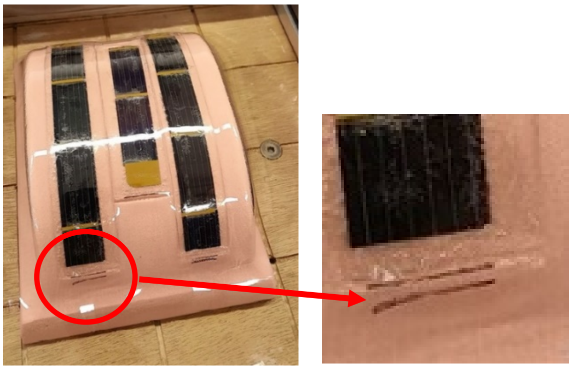

Figure 16 Displacement of a solar strip

To understand the process, three encapsulated solar strips where marked on the PETG and the end of the strip. Filming the process, the marking didn't move the first seconds, so the strip moved with the PETG when that was stretched. In the final stage of stretching, after 7 seconds and a temperature of ≈ 100°C, the marking moved. During cooling down further the distance between the marking remained constant indicating that the solar strip was fixed to the PETG.

Initially small solar foils where used, but when a large product was made with a complete submodule, 29x22 cm, the module was detached after a few hours, as the PETG continues to shrinks even when at room temperature. Using an acrylic adhesive on PET gave better adhesion, but still gave considerable stress on the solar foil. Therefore, an intermediate stress relief layer was used.

Finite element calculations learn that a combination of polyolefin and polyurethane on the PET-barrier of the solar foil could be a solution to release the stress caused by the cooling of the PETG. PU diminishes the stress of the PETG, while PO has a small Young's modulus and converts the residual stress in deformation.

Figure 17 Solar Foils
directly on PETG with intermediate PO/PU

In Figure 17 can be seen that most of the stress is relieved in the PO/PU-layer. Further progress is expected from a better adhesive on top of the PU.

In Figure 18 can be seen that the solar module and its interconnects withstand the stretching in the process and that a curved surface (closer to the lamp) shows a good performance.

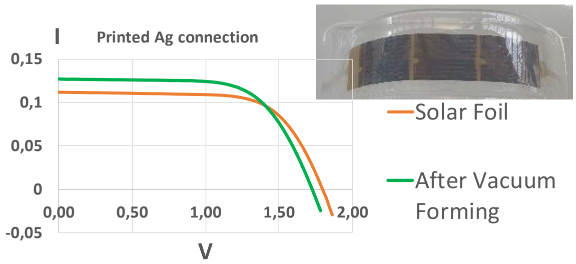

Figure 18 Performance before and after vacuum forming

6 COMPOSITES

With composite materials very large elements can be made such as bridges, pavement of solar roads and wind turbine blades. This is a limitation of injection moulding and vacuum forming. Another advantage is the absence of thermal stress as the processes are at room temperature or slightly above. Adhesion of PET to the resin is obviously still a requirement.

In this study an inventory was made of suitable techniques to integrate solar foils in composite products.

Table 2 Inventory of techniques to integrate solar foils with composites

Methods	Pro's	Con's
Hand Layup	- No high tech equipment - Simple method	- Lots of air bubbles enclosed in the resin
Vacuum Bagging	- Amount of air bubbles minimized - Easy control of resin distribution through the fibers	- Vacuum pomp - Knowledge and experience
Vacuum Infusion	- Amount of air bubbles is minimized - The flow can be adjusted for different configurations	- Complicated process - Knowledge and experience - Vacuum pomp and suitable resin

In Table 2 are the three most suitable techniques depicted. Experiments are performed to test the feasibility of these techniques. It turned out that with a hand layup too many air bubbles were enclosed in the product. This is aesthetically unacceptable and may have an influence on lifetime and strength of the composite.

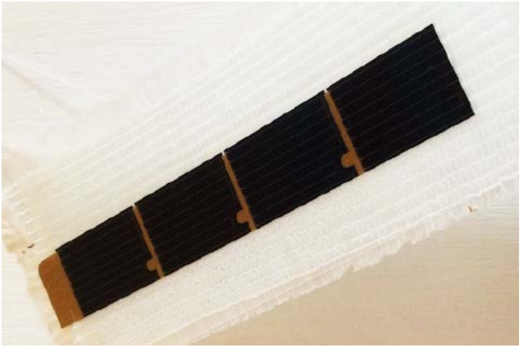

Figure 19 Solar Foil in composite using vacuum infusion
Back glass fiber and polyester
Front glass fleece and polyester

In vacuum infusion the resin is drawn through a dry stack of fibres using vacuum. The flow of resin through the fibres must reach the complete fibre package, so the position of the inlet, the quantity of resin and viscosity that increases in time must be well controlled. So, in this case a simple flat product is made on a flat surface.

Figure 20 Solar foil in composite using vacuum bagging

In vacuum bagging the fibre layup is impregnated with resin. The vacuum is used to remove the excess of resin. Complex and large products can be made. In Figure 20 on the left the mould with the layup is shown. On the right the resulting product is shown. The mould is negative as this results in a smooth surface on the sunny-side.

In damp heat tests, 1000 hours, the solar module doesn't delaminate from the composite.

7 CONCLUSION

With flexible solar foils curved products can be made of different sizes and plastic materials. These solar powered products can be made with injection moulding, polycarbonate and possibly polypropylene, with vacuum forming, using an intermediate flexible layer and composite, preferably with vacuum bagging. As the solar foils are usually laminated in PET-foil that has a very low coefficient of thermal expansion, shrinkage cannot be accommodated by solar foils. It is needed to find foils that protect the solar foil, possibly with a limited lifetime, as long it survives the product, that allow shrinkage.

8 ACKNOWLEDGEMENTS

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