Development of thermocompression process to integrate photovoltaic cells in a double-curved composite structure: model and experimentation

Tatiana Duigou, Vincent Boichon, Fabien Chabuel, Gilles Dennler, Pascal Francescato, Georges Habchi, Manuel Lagache, Philippe Saffré, Lionel Tenchine, Julien Gaume

Développement d'un procédé de thermocompression permettant d'intégrer des cellules photovoltaïques dans une pièce à double courbure : modélisation et mise en œuvre

Development of thermocompression process to integrate photovoltaic cells in a double-curved composite structure: model and experimentation

Tatiana Duigou[1,2,3], Vincent Boichon[3], Fabien Chabuel[1], Gilles Dennler[3], Pascal Francescato[2,3], Georges Habchi[2], Manuel Lagache[2], Philippe Saffré[2], Lionel Tenchine[3], Julien Gaume[1]

1 : DTS, SMPV, LAM
CEA, LITEN, Université Grenoble Alpes
F-38000 Grenoble, France
e-mail : tatiana.duigou@cea.fr

2 : Laboratoire SYMME
Université Savoie Mont Blanc
FR 74000 Annecy, France

3 : Centre Technique Industriel de la Plasturgie et des Composites (IPC)
01100 Bellignat, France

1. Introduction

Greenhouse gas emissions have almost doubled since 1970 and the transport sector emits 14% of these emissions. In this context, the automotive sector is encouraged to propose alternative solutions to gas-powered vehicles. The current trend to tackle this issue is to electrify vehicles, usually using high capacity batteries. However, these popular technologies of Electric Vehicles (EVs) require a large amount of lithium for their heavy batteries. Thus, the integration of PhotoVoltaic (PV) modules as body parts for hybrid or electric vehicles could allow to extend the vehicle's range while reducing the battery size [1].

2. Topics and investigations

The automotive industry is changing to lightweight materials and more energy-efficient vehicles. PV modules have a potential market in this transition. Rigid PV panels integrating silicon cells built directly into the car body outperform thin flexible solar films in terms of efficiency and reliability. This rigidity is usually brought by glass. To increase the integration of PV modules into the car, the use of composite materials is an interesting option, as they offer an efficient combination of mechanical performances and lightweight. However, the brittle behaviour of the cells and the necessary achievement of certain optical characteristics are incompatible with the usual manufacturing processes of composite panels yet. As well, lamination, which is the traditional process of the photovoltaic industry, restricts the possibilities of integration in automotive parts. These parts may have complex shapes like double curvature and stiffeners which are poorly compatible with lamination. Thus, this study focuses on the development of an alternative manufacturing process for the production of composite double-curved PV modules and the study of thermomechanical stresses resulting from this process.

A previous part of this research work enabled to identify a process which offers an alternative to the lamination process: the thermocompression. It allows to produce curved photovoltaic modules made of composites, and adapts to the automotive industry constraints.

This study tackles both the adaptation of this process to integrate photovoltaic cells, and the simulation of the thermocompression process with a finite element calculation tool. The numerical model aims at optimizing the process parameters and module stack to limit residual stresses while minimizing the weight of the structure.

3. Aims

The main obstacles to Vehicle Integrated PV (VIPV) are:

- The need to maximize the photovoltaic modules power output.
- Like most body parts, the structure integrating PV cells may present a double curvature to which monocrystalline silicon cells are poorly adapted [1].
- The mechanical requirements for automotive parts: the body parts need to withstand a set of loads to which PV cells are not suited. The design and process of integration should take into account the minimization of stresses for the cells.
- The weight of the PV module: as it is supposed to provide energy to the vehicle, the integration of photovoltaic cells should not penalize the weight of the vehicle to maximize the vehicle range allowed by the energy intake of the PV module. The use of an optimized composite structure can make the achievement of this aim easier.
- The cost of production of automotive body parts, even if they integrate more functionalities.

Technologies of solar-powered cars already exist but they mostly use glass encapsulation to protect the cells, thus not minimizing the weight and optimizing the mechanical performances of the module. To keep a competitive product, it is further envisaged to design the composite structure integrating PV through a "one-shot" process. It should guaranty the previous specifications and minimize the strain and residual stresses due to the heterogeneity and non-symmetry of the structure [2]–[4].

This study considers a composite structure with double-curvature integrating silicon solar cells. The aim is both to adapt the thermocompression process to the integration of Si cells in composite materials and to propose a predictive model of the residual stresses implied by this process. The numerical model enables to optimize the stack and processes parameters in order to minimize residual stresses, minimize the structure weight and optimize the mechanical performance of the structure. This model is validated with mechanical experimental tests on parts produced by the thermocompression process developed in this study. Complementary tests aim at validating the electrical performances and ageing behaviour of the PV modules with regards to IEC 61215 standard.

4. Methods and results

4.1 Process development

A preliminary study was made to select materials adequate for the thermocompression process.

First experimental tests were operated with a planar mold and enabled to identify materials and process parameters allowing to produce composite PV modules presenting no electrical failure.

This work fed a set of specifications for the design of a double curvature mold compatible with the thermocompression process and enabling to integrate PV cells. Further work enabled to produce double curved PV modules showing no cell failure.

After these encouraging results, it was necessary to optimize the process parameters and stack to minimize weight and the internal stresses resulting from the process. A Design Of Experiment on this validated simulation work enabled identifying the best stack candidates and process parameters.

4.2 Numerical model

The numerical model is designed with a Finite Element Analysis software -ANSYS- to describe a module integrating the solar cells in sheets of polymer encapsulant. The front sheet is either made of a polymer sheet, or of glass-fibre pre-pregs. The back sheet is made of glass fibre-based thermoplastic pre-pregs. These materials allow to withstand the loads and protect the cells from the environment.

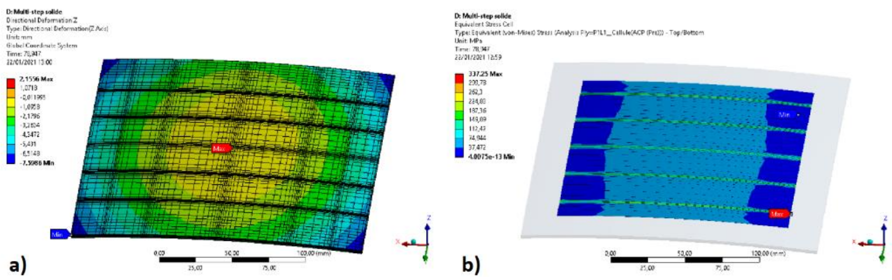

Figure 1-a) Z deformation and mesh for a double curved cell. b) Stresses in the cell resulting from the cooling in the mold

Due to symmetries and periodicity of the structure, loads and boundary conditions, the representative pattern is composed of one cell. This is representative of a 4-cell module. The model uses hexahedral solid elements with adapted sizing (fig. 1a). The setup is adapted for a parametric analysis exploring the influence of materials, thickness, ply orientations, number of plies ... on the stiffness and strength of the whole structure. A multi-step thermomechanical analysis modelling the whole process is performed. A first analysis was led to identify the simplifications which could be applied, passing from the physical steps of the process to their numerical implementation (fig. 2). It simulates 3 steps of the process:

1. Application of the double cuvature to the cells, front and back sheet materials being inactive because they are not processed at this step. The thermal condition is 230°C.
2. Cooling of the stack in the mold. The front and back sheet plies are active and have temperature dependent behaviors. The temperature goes down from 230°C to 50°C.
3. Opening of the mold at 50°C. This step enables to quantify the residual deflection and stresses coming from the thermocompression process.

This parametric model enables an optimization of this non-symmetric structure to fulfil the following objectives:

- The minimization of residual thermomechanical stresses resulting from the process. This process especially implies residual stresses coming from the curvature of the cells, and differential deflection between the front and back sheets -especially in the case of a polymer front sheet during the cooling phase.

- A representative thermal load, representing a thermal cycle of the international standard for PV modules IEC 61215;
- Equivalence of the bending stiffness to that of a car roof;
- Mechanical strength of the cell and of the interconnections.

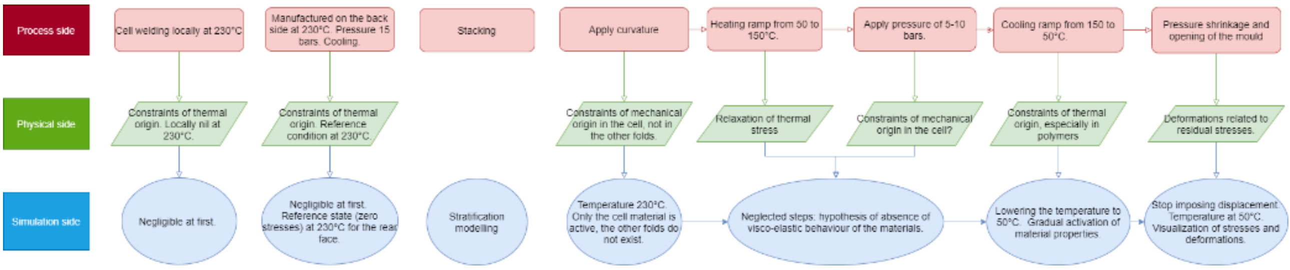

Figure 2- Going from process steps to the numerical implementation of the multi-step model.

This exploration is led with a design of experiment method, which especially aims at minimizing interfacial and internal stresses (fig. 1b).
The parametrical aspect of this simple model enables to scan a large number of configurations and to identify the most critical parameters among the number of plies, their orientation, the nature of the resin and of the encapsulant.

4.3 Experimental tests

This model was validated by a set of experiments on double curved modules of dimensions 40 cm x 40 cm (fig. 3). The double curvature radii of the module are 1 and 2 meters, this is the upper boundary that is envisaged for automotive body parts.

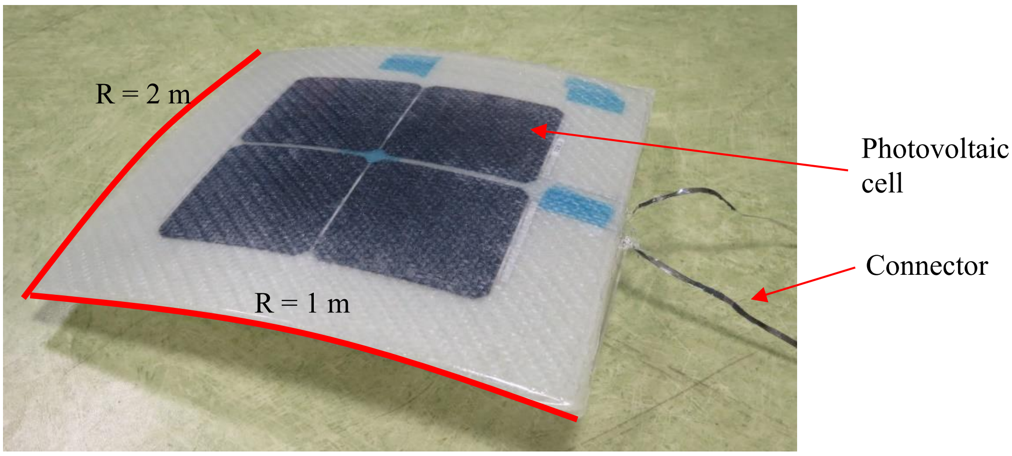

Figure 3- PV module of 40 cm x 40 cm.

Various materials have been used for the double-curved modules which were produced, including:

- Glass fibre thermoset and thermoplastic prepregs fabrics for the front and back sheets;
- Thermoplastic polymers for the front sheet;
- Different thermoplastic encapsulants.

Several tests have been performed.

- The first one aims at validating the deformed shape of the module at the outlet of its processing by means of laser metrological measures. This test enables to validate the numerical model, especially the deformation of the stack after the process.
- The second ones consist in mechanical tests. They enable to evaluate the bending stiffness of the overall structure and the load for the first damage. Impact tests were also performed. These test validate the mechanical behavior of the module for some tests representative of some automotive qualification tests.
- Complementary electrical tests were performed to assess the reliability of the PV modules produced by thermocompression, especially their electrical behaviour under bending and during ageing tests. The structure was qualified with standard photovoltaic qualification equipment, including spectrophotometry, electroluminescence and light I-V measures before and after tests in climatic chambers (norm IEC 61215). They enable to evaluate and optimize the power supply of the panel, choosing the most appropriate materials for the front sheet.

6. Conclusion and perspectives

This study focused on the adaptation of a thermocompression process to integrate photovoltaic cells. It considers both the experimental process development, and its simulation with a finite element analysis software. PV modules produced with this process were used for the experimental validation of the numerical model. The experimental tests validate the thermomechanical multistep model. This predictive model allows to optimize the composite layout and process parameters to minimize residuals stresses. Complementary experimental tests evaluate the electrical performances and ageing behaviour of the PV module with regards to IEC 61215 standard.

According to our results, a composite structure integrating photovoltaic cells appears to be an interesting alternative to traditional glass structures, both in terms of mass and compatibility with the constraints of the automotive industry. Thus, the process developed could be applicable to either the automotive industry or any application needing lightweight and curved PV modules. Further research will aim at proposing an industrial scheme for this process.

7. References

[1] K. Araki, L. Ji, G. Kelly, et M. Yamaguchi, « To Do List for Research and Development and International Standardization to Achieve the Goal of Running a Majority of Electric Vehicles on Solar Energy », Coatings, vol. 8, no 7, p. 251, juill. 2018, doi: 10.3390/coatings8070251.

[2] C. González, J. J. Vilatela, J. M. Molina-Aldareguía, C. S. Lopes, et J. LLorca, « Structural composites for multifunctional applications: Current challenges and future trends », Prog. Mater. Sci., vol. 89, p. 194-251, août 2017, doi: 10.1016/j.pmatsci.2017.04.005.

[3] E. H. Amalu, D. J. Hughes, F. Nabhani, et J. Winter, « Thermo-mechanical deformation degradation of crystalline silicon photovoltaic (c-Si PV) module in operation », Eng. Fail. Anal., vol. 84, p. 229-246, févr. 2018, doi: 10.1016/j.engfailanal.2017.11.009.

[4] U. Eitner, « Thermomechanics of photovoltaic modules », Zentrum für Ingenieurwissenschaften der Martin-Luther-Universität Halle-Wittenberg, 2011.

Aknowledgment

This work was co-financed by IPC and CEA. It has been realized with the participation from members of the SYMME laboratory and INES.2S and received funding from the French State under its investment for the future programme with the reference ANR-10-IEED-0014-01.