



D3.10 – Flexible machine for automated stacking and lamination of curved VIPV panels manufacturing

Task 3.11: Flexible machine for automated stacking and lamination of curved VIPV panels.



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Summary of SEAMLESS-PV PROJECT

A novel manufacturing process for integrated photovoltaics

Integrated photovoltaics (IPVs) have demonstrated their success and impact in their use as building-integrated photovoltaics. They are also considered promising in several other sectors. Their adaptation to other industries or devices could offer surprising benefits. Unfortunately, the very need for adaptable IPV solutions hinders their expansion as their current manufacturing processes cannot create IPV solutions customised to each sector. The EU-funded SEAMLESS-PV project aims to tackle this by developing revolutionary tools for photovoltaic manufacturing as well as new IPV products that offer improved efficiency, adaptability and integrability while at the same time showcasing their cost-effectiveness in comparison to competitors.

The title of SEAMLESS-PV project is *“Development of advanced manufacturing equipment and processes aimed at the seamless integration of multifunctional PV solutions, enabling the deployment of IPV sectors”*. SEAMLESS-PV is a Horizon Europe Innovation Action started in January 2023 that will continue through December 2026.

More information can be found at:

<https://www.seamlesspv.eu/>

<https://cordis.europa.eu/project/id/101096126>

EXECUTIVE SUMMARY

This deliverable presents the work carried out under task T3.11: Flexible machine for automated stacking and lamination of curved VIPV panels, focused on developing the manufacturing process required for the automated production of curved panels suitable for Vehicle Integrated Photovoltaics (VIPV) applications.

The development has addressed two key aspects:

1. Tool for 3D Lay-Up of Matrix.

A flexible gripper has been designed and implemented, capable of handling different sizes and curvatures without requiring tool changes. MASS has filed a patent application for this innovative gripper concept.

2. Lamination of 3D Panels.

MASS has developed a laminator that can be classified as a laboratory laminator rather than a prototype. It offers specifications that enable processing flat or large-volume laminates (up to 150 mm height) while ensuring precise control of temperature (upper and lower) and pressure. A laminating cycle for curved panels has been successfully defined using this laminator, specifically for a hood designed by Lightyear (LYL).

This work represents a significant step toward enabling automated production of curved VIPV panels, combining flexibility, precision, and scalability in the manufacturing process.

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1 INTRODUCTION

1.1 Description of the deliverable content and purpose

This document presents the procedures undertaken and the results obtained during the development of two essential processes aimed at automating the manufacturing of curved panels: **stacking** and **laminating**.

The purpose of this work is to enhance production efficiency, ensure consistency in quality, and reduce manual intervention by implementing reliable and scalable automation solutions. The following sections provide a detailed description of the methodology applied, the challenges addressed, and the outcomes achieved throughout the development phase.

1.2 Relation with other activities in the project

Table 1.1 depicts the main links of this deliverable to other activities (work packages, tasks, deliverables, etc.) within SEAMLESS project. The table should be considered along with the current document for further understanding of the deliverable contents and purpose.

Table 1.1: Relation between current deliverable and other activities in the project

Project activity	Relation with current deliverable
T3.11	The current deliverable feeds from all project activities and work packages.

1.3 List of abbreviations

Table 1.2: List of abbreviations

Acronyms	Meaning
Max	Maximum
Min	Minimum
T ^a	Temperature
VIPV	Vehicle Integrated Photovoltaics

2 GENERAL 3D PANEL VIEW.

As a preliminary step, a comprehensive 3D simulation of the current curved panel manufacturing process was carried out. This simulation provided a detailed visualization of the workflow and allowed the identification of two key stages selected for technological development: C (stacking) and D (final product lamination).

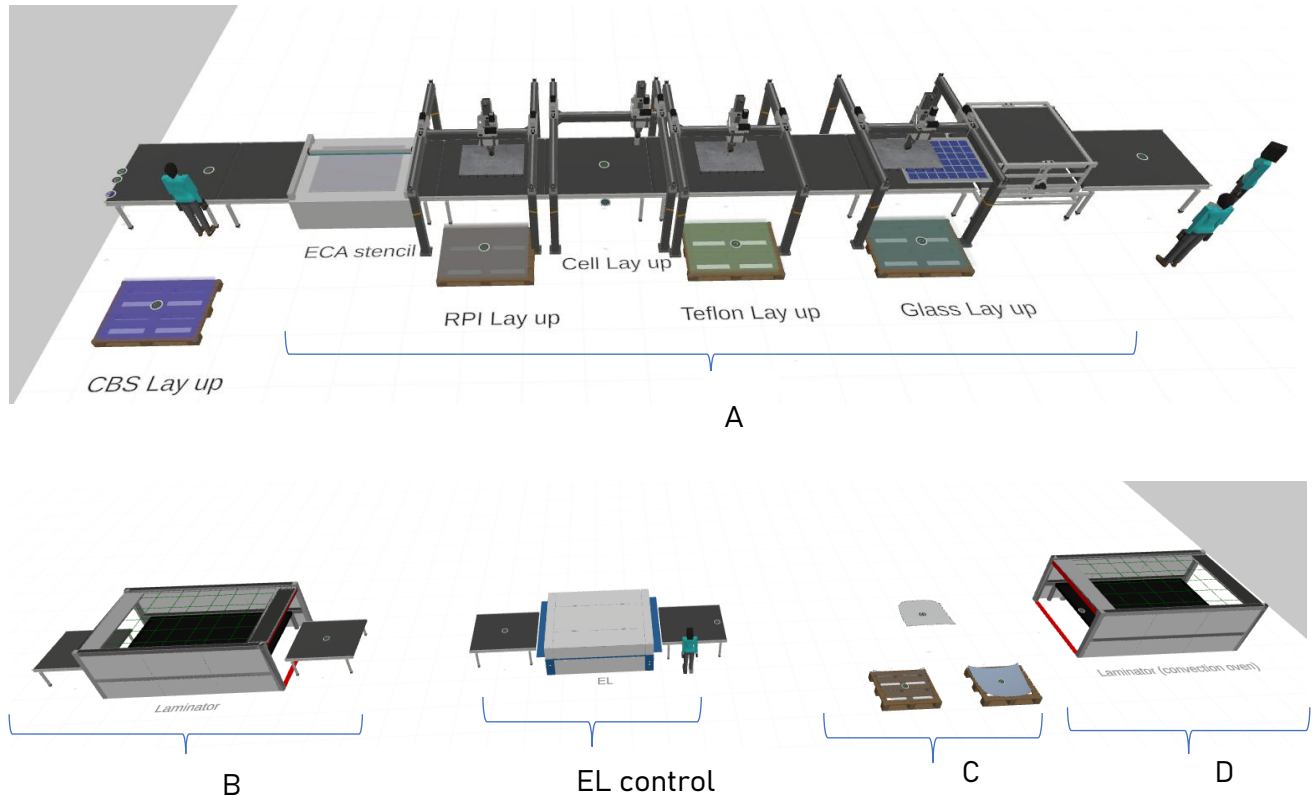


Figure 2.1: Current process (Images obtained from the process simulation).

The process begins with the production of the flat solar matrix (A). This matrix is then cut to shape, including specific cuts that enable it to conform to the 3D curvature of the glass, and subsequently laminated (B). Following this, a layup is prepared consisting of glass, encapsulant, solar matrix, encapsulant, and back structure (C). The assembly is vacuum bagged and subjected to a second lamination cycle in a convection oven (D).

3 TOOL FOR 3D LAY-UP OF MATRIX (STACKING)

3.1 Definition of specifications

The initial step consisted of defining, in collaboration between MASS and LYL, the specifications that will serve as a reference framework for the development of the **stacking** process prior to lamination.

Table 3.1: Tool for 3D lay-up of matrix specifications.

Definition of specification	Range/value to achieve	Achievement
3D Lay-up	Maximum dimension 1200 mm x 700 mm Minimum--> 600 mm x 166 mm	Necessary
	Accuracy--> 0.5 mm	
	Max height difference 150 mm	
	Curve type--> natural curve	

3.2 Product/process development

The development of this aspect has led MASS to file patent number EP24383182, which protects a system for transporting strings and foils for non-flat modules. Within task T3.11, MASS has worked on two operating modes, as illustrated in the following images:

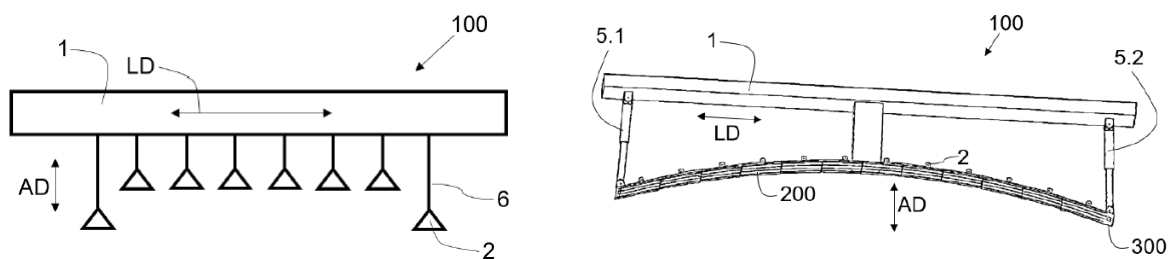


Figure 3.1: Patent number EP24383182 images

1. Mode 1 → Defined by a number of suction cups that move independently by means of cylinders.
2. Mode 2 → Defined by the creation of a plane with fixed dimensions (non-adjustable), but flexible, and the application of vacuum to hold the element to be positioned in a curved shape (foil or string).

3.2.1 Mode 1

For the design of this system, suction cups were selected that allow both rotation and displacement through the inclusion of bellows within the suction cup (see image).

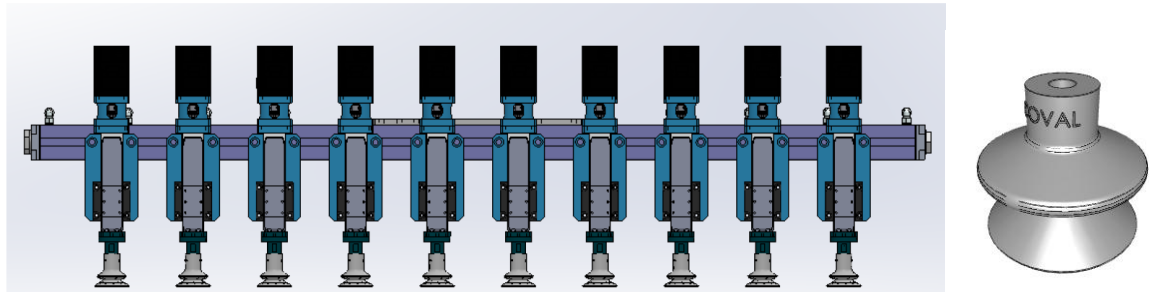


Figure 3.2: Mode 1 tool 3D design.

This system has been tested on a robot with a string, which is more difficult to handle than foil.

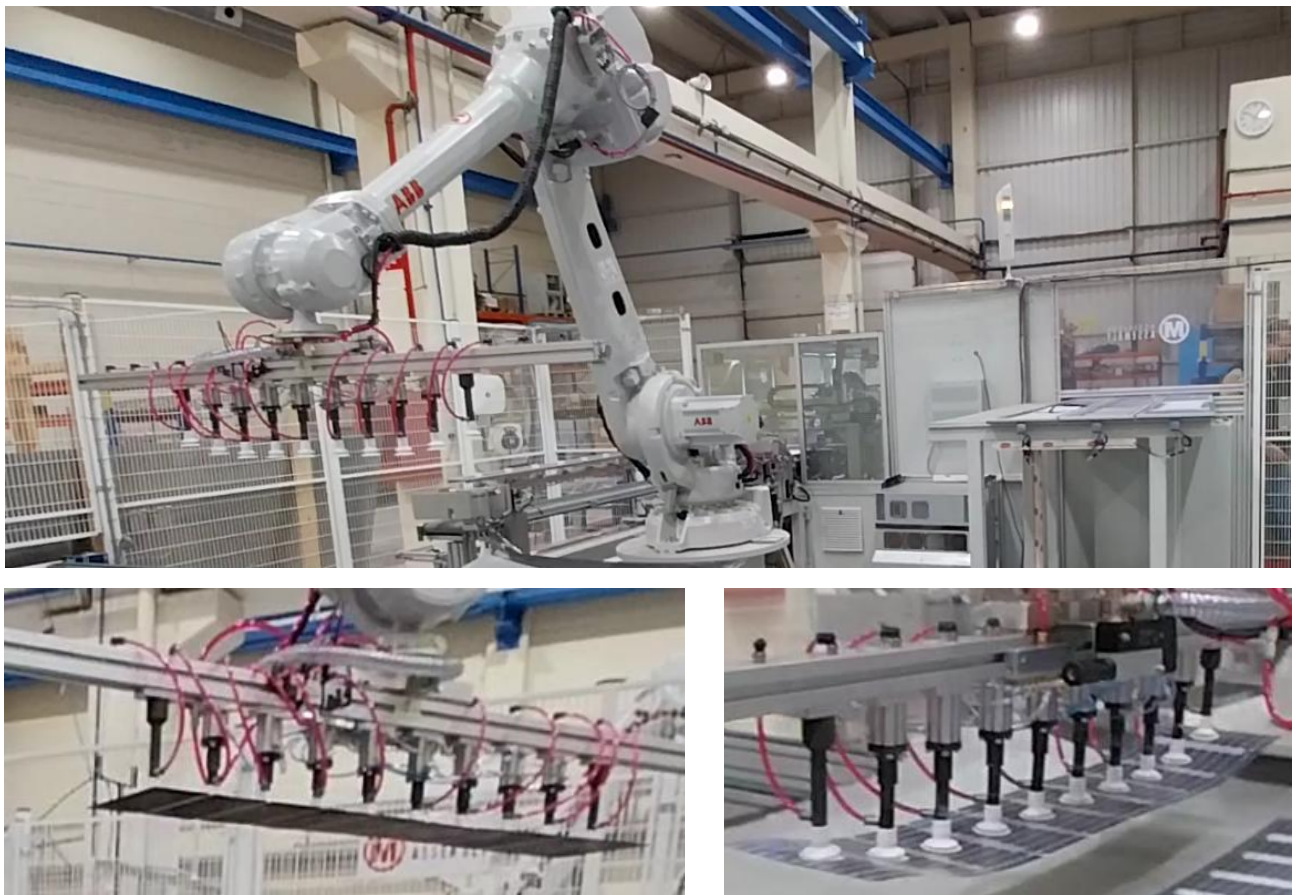


Figure 3.3: Tool test in robot.

The 3D design of the foil tool was carried out.

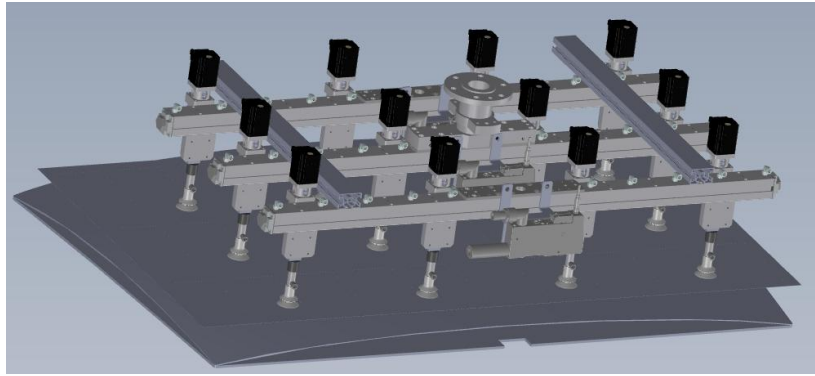


Figure 3.4: Mode 1 tool for foil 3D design.

3.2.2 Mode 2

For this system, the starting point was the definition of a plane with non-variable dimensions. Initial tests were carried out using sheets of 0.2 mm and 0.5 mm thickness, and it was observed that both behaved similarly when a string was attached.

As a second step, the method for applying vacuum to the sheet was studied, with several options considered. System 1 and 3 were selected, and a prototype of each was developed based on this approach.

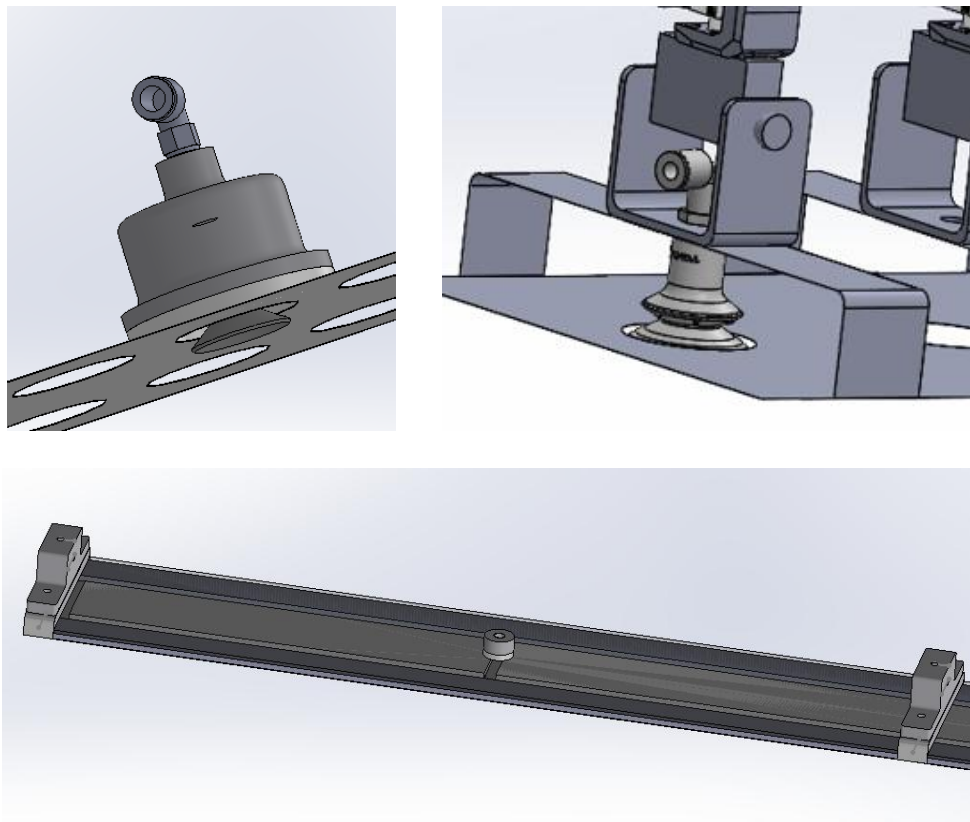


Figure 3.5: Samples of mode 2 tool 3D designs.

The prototypes were tested with a string of cells and the system 3 showed potential to become the final solution, although some improvements were identified, such as preventing leaks, using more

flexible materials, and incorporating more robust components to enable integration with a handling system (robot, weight compensator, etc.).

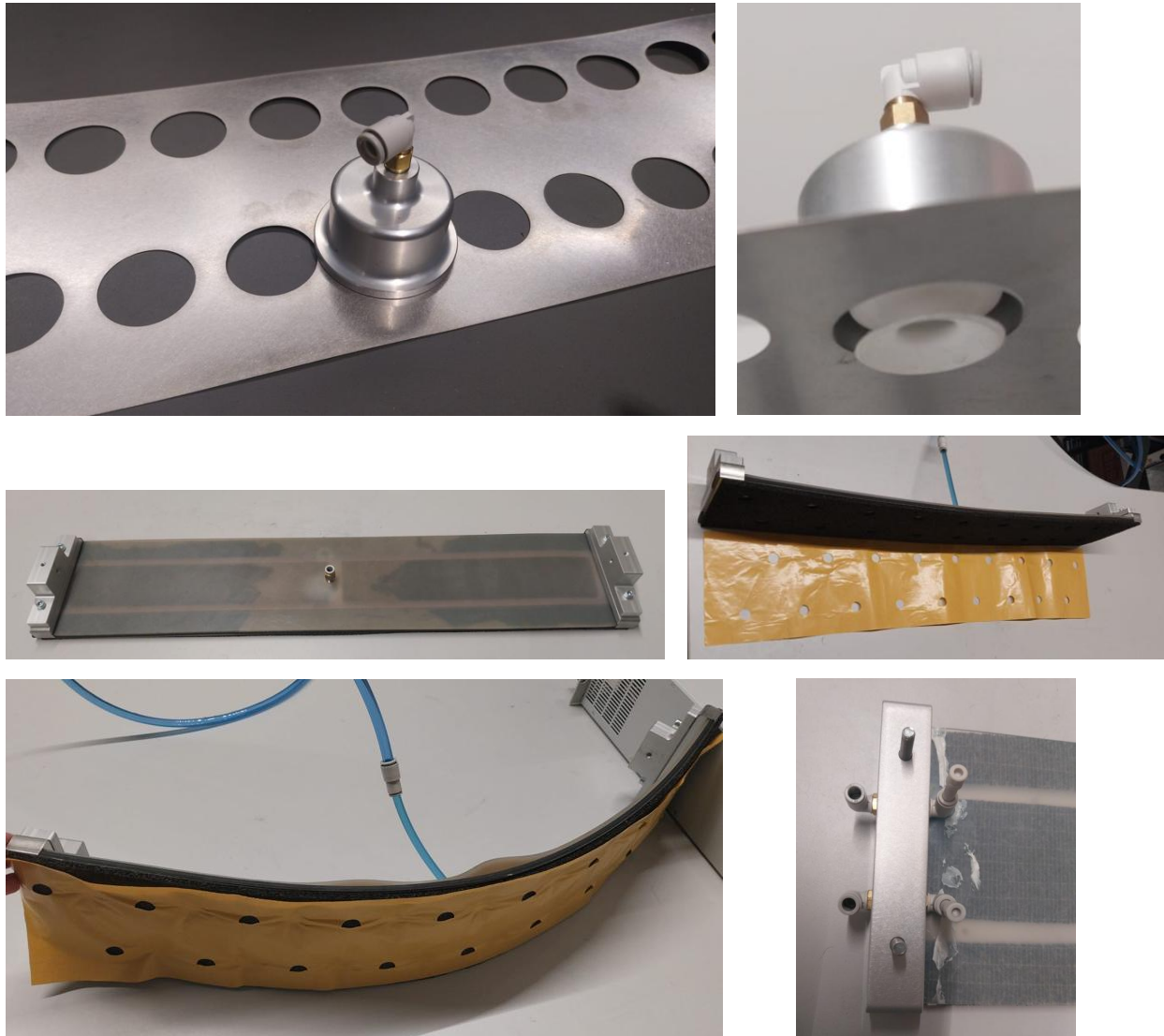


Figure 3.6: Mode 2 tool prototypes.

The aim of this system is to create a tool that is modular and adaptable to different string/foil geometries.

3.3 Compliance with specifications

Table 3.2: Tool for 3D lay-up of matrix specifications.

Definition of specification	Range/value to achieve	Achievement
3D Lay-up	Maximum dimension 1200 mm x700 mm Minimum--> 600 mm x 166 mm	Yes, in both cases, it is a system scalable to the required dimensions.
	Accuracy--> 0.5 mm	Depend on the robots used
	Max height difference 150 mm	Yes, can be more
	Curve type--> natural curve	Yes, mode 2 respect this more than the mode 1

4 LAMINATION OF 3D PANELS.

4.1 Definition of specifications

The initial step consisted of defining, in collaboration between MASS and LYL, the specifications that will serve as a reference framework for the development of the process, in this case the final lamination.

Table 4.1: Laminator specifications.

Definition of specification	Range/value to achieve
Material to be process	Glass/encapsulant/solar matrix/encapsulant/back structure
Dimension (Length, width, height)	Max--> 1500 mm, 1000 mm, 150 mm.
	Min--> 300 mm, 300 mm, 0 mm
T ^a max	150 °C
Cycle time	21 min
Pressure	Max--> 1000 mbar positive in upper chamber (membrane)
Opening mode	Vertical opening. Stroke 800 mm, for maintenance & Upgrades
Lamination steps	1
Heating medium	Thermal oil in combination with steel heating platens and flexible membrane
Type of cooling	Cooling platen double side or fan cooling
Quality	97%

4.2 Product/process development

To develop the lamination cycle for a 3D product, the following steps were followed:

- Definition of the part to be laminated
- Definition of the laminator specifications
- Definition of the lamination tool
- Laminator manufacturing
- Laminator optimization and setup
- Laminating tool manufacturing
- Definition of the 3D printed part lamination cycle

4.2.1 Definition of the part to be laminated

After analysing different options, MASS and LYL decided to work on the hood, the highest piece of those proposed as possible options.

Table 4.2: Parts with solar panel.

	<u>Lightyear 0</u>		
	Hood	Roof	Tailgate
External dim. [cm]	156x124	135x180	127x129
Surface area [m2]	1.69	2.31	1.57

4.2.2 Definition of the laminator specifications

Considering the intended purpose of the laminator, a set of specifications was established. The most relevant specifications are presented below:

1. Working area: 2500 mm x 1500 mm.
2. Maximum height (of the laminating chamber and at which the membrane has to work)--> 150 mm.
3. Transporting system: INCLUDE A TRANSPORT SYSTEM 305 KG Carrier (lamination tool).
4. Electrical heating (down and upper) for better control.
5. Same inlet and outlet conveyor

4.2.3 Definition of the laminating tool

This section focuses on the design, material selection, and heating method of the tool. These considerations resulted in the final design shown below, manufactured in aluminium due to its high thermal conductivity.

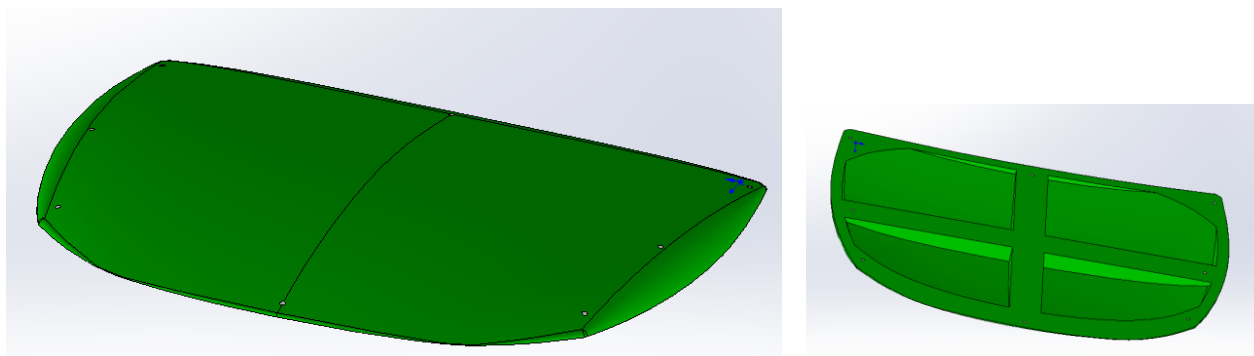


Figure 4.1: Laminating tool 3d design.

4.2.4 Laminator manufacturing optimization and setup

During this phase, the laminator was manufactured, an initial machine setup was performed, and subsequent optimizations were implemented to enable the definition of the lamination cycle for a 3D product.



Figure 4.2: Laminator.

4.2.5 Laminating tool manufacturing

The tool was manufactured to perform 3D lamination, according to the 3D defined above.



Figure 4.3: Laminating tool.

4.2.6 Definition of the 3D printed part lamination cycle

At this stage, 10 separate experimental runs were performed with each one introducing a process improvement over the last to find a set of parameters which will yield a fully laminated hood panel without major defects (e.g. cracked glass and bubble formation within the encapsulant).

LYL and MASS agreed beforehand that the most logical way to proceed with the runs is to first laminate LYL's rear stack (i.e. without the cells) in MASS' 3D laminator to find the optimized parameters which yield panels without significant defects. After finding the best process window, MASS will then laminate LYL's full solar matrix (i.e. rear stack with cells) to determine if the parameters that worked on the foils without the cells also works for those with the cells.

In essence, the first 6 runs of the investigation (i.e. Test # 1 – Test # 6) dealt with the lamination of the rear stack alone while the last 4 runs dealt with the lamination of the complete solar matrix. A handful of details of some of the runs are shown in the table on the next page.

Table 4.3: The parameters used by MASS in laminating LYL's rear stack (Test # 1 – Test # 6) and solar matrices (Test # 7 – Test # 10) using their 3D laminator. For brevity, the details of some of the runs are not shown in the table.

TEST #	TEMP SET	VACUUM, s	LAMINATION 1 TIME	LAMINATION 1 VACUUM, kPa	LAMINATION 2 TIME	LAMINATION 2 VACUUM, kPa	LAMINATION 3 TIME	LAMINATION 3 VACUUM, kPa	LAMINATION WITH COMPLETE SOLAR MATRIX?	COMMENTS
1	TS	360	L1	-80	L2	-50	L3	-5	No	• Displacement of the stacked layers during lamination. • Glass breakage
6	< TS	720	L1	-90	> L2	-65	< L3	-40	No	• No cracks detected • No bubbles
7	< TS	720	L1	-90	> L2	-65	< L3	-40	Yes	• No cracks detected • Bubbles only in half of the module • All electrical circuits are functional
8	< TS	420	L1	-90	>> L2	-25	0	0	Yes	• Cracks detected
10	< TS	600	L1	-90	> L2	-65	>> L3	-40	Yes	• Only one edge crack is detected • Barely any bubbles are visible

Of all the runs, Test # 10 yielded the best process parameters in laminating LYL's hood panel because it did not impart bubbles to the module and there was only a single crack at the edge of the panel which was hypothesized to be due more to a glass defect than due to the lamination procedure itself (see Figure 4.4).



Figure 4.4: The laminated module using Test # 10 processing parameters.

4.3 Compliance with specifications

Table 4.4: Laminator specifications.

Definition of specification	Range/value to achieve	Achievement
Material to be process	Glass/encapsulant/solar matrix/encapsulant/back structure	Yes
Dimension (Length, width, height)	Max--> 1500 mm, 1000 mm, 150 mm.	Yes
	Min--> 300 mm, 300 mm, 0 mm	Yes
T ^a max	150 °C	Yes
Cycle time	21 min	Yes, it can be reduce using two steps laminator
Pressure	Max--> 1000 mbar positive in upper chamber (membrane)	Yes
Opening mode	Vertical opening. Stroke 800 mm, for maintenance & Upgrades	Yes
Lamination steps	1	Yes
Heating medium	Thermal oil in combination with steel heating platens and flexible membrane	Electrical heating, for better control
Type of cooling	Cooling platen double side or fan cooling	Yes, fan

Quality	97%	To be tested during production. As a laboratory scale laminator is not easy to measure this value.
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5 CONCLUSIONS

Following the development work carried out, the feasibility of implementing innovative solutions in two critical processes for large-scale manufacturing of 3D panels within photovoltaic module production has been confirmed.

1. Stacking Process

- A gripper system has been designed and validated, capable of handling both strings and foils, ensuring precise positioning on tools with concave and convex geometries.
- The design incorporates adaptive mechanisms that enable safe manipulation of components with varying curvatures, preserving material integrity throughout the process.
- This development has reached a level of innovation that resulted in a patent application, reinforcing its distinctive nature and industrial applicability.

2. Laminator for Curved Panels

- A laminator specifically designed for 3D products has been developed, capable of addressing the challenges of laminating non-flat geometries.
- During design and validation, critical factors for process optimization have been detected and improved, including:
 - **Chamber opening:** increased height required to accommodate curved panels.
 - **Flexible membrane:** improved adaptability to ensure uniform contact.
 - **Thermal management:** more accurate temperature control to optimize adhesion and minimize internal stresses.
- Additionally, a dedicated 3D tool has been developed with the appropriate characteristics to support the lamination process, ensuring dimensional stability and efficient thermal transfer.
- A lamination recipe has been defined, which can serve as a starting point for serial production of curved panels.



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