Centre adscrit a la

Mechanical Engineering Bachelor.

INTEGRATION OF A UV SOURCE FOR LIGHT-BASED CURING OF CONTINUOUS FIBRE COMPOSITES IN THE PULTRUSION PROCESS.

Bachelor's Thesis

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Motivation

My enthusiasm for composites in Formula Student drives me to explore novel applications. Transitioning to UV-based pultrusion is thrilling, opening a new branch in materials engineering. With prior experience in automotive composites, I'm confident this will innovate lightweight, strong component manufacturing, enriching my skills and technological advancement.

The field of composite profile pultrusion is vast, and various universities and research centres have begun studying and producing different pultrusion lines that cure composites using UV light. This method offers some advantages over conventional methods. Conventional pultrusion limits speed and efficiency in composite curing, whereas UV light curing excels in speed, precision, and control, eliminating heat and reducing production times. UV light enhances quality and reduces waste by allowing selective curing and working with heat-sensitive materials. This conversion promises not only efficiency but also higher-performing composites.

Acknowledgments

I would like to thank my family for giving me the opportunity to study at the TecnoCampus University and I would also like to thank them for their support during these four years of my journey including all the professors. Finally, I would also like to thank IAESTE for giving me the opportunity to do an internship at the ILK of the TU-Dresden.

Abstract

This study focuses on the integration of a UV source for light-based curing of continuous fibre composites in the pultrusion process. The research investigates how composites can be effectively cured using ultraviolet light within the pultrusion industry. A specialized mold for the pultrusion line was designed and subjected to various experiments. Based on the experimental results, a redesign of the mold was implemented. The new design enhances the curing process by incorporating UV lamps on both sides of the mold, ensuring even light exposure.

Resum

Aquest estudi es centra en la integració d'una font UV per al curat mitjançant llum de compostos de fibra contínua en el procés de pultrusió. La investigació examina com els compostos poden curar-se eficaçment utilitzant llum ultraviolada en la indústria de la pultrusió. Es va dissenyar un motlle especialitzat per a la línia de pultrusió i es van realitzar diversos experiments en ell. Basant-se en els resultats experimentals, es va implementar un redisseny del motlle. El nou disseny millora el procés de curat mitjançant la incorporació de làmpades UV a ambdós costats del motlle, assegurant una exposició uniforme a la llum.

Resumen

Este estudio se centra en la integración de una fuente UV para el curado mediante luz de compuestos de fibra continua en el proceso de pultrusión. La investigación examina cómo los compuestos pueden curarse eficazmente utilizando luz ultravioleta en la industria de la pultrusión. Se diseñó un molde especializado para la línea de pultrusión y se realizaron varios experimentos en él. Basándose en los resultados experimentales, se implementó un rediseño del molde. El nuevo diseño mejora el proceso de curado mediante la incorporación de lámparas UV en ambos lados del molde, asegurando una exposición uniforme a la luz.

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Glossary

UV	Ultraviolet
PRFV	Reinforced Polyester with Fiberglass
LED	Light-Emitting Diodes
Io λ	Incident intensity at a specific wavelength (W/m²)
IT λ	Transmitted intensity at a specific wavelength (W/m²)
A λ	Absorbance at a wavelength specific concentration of photoinitiator system
LUX	Luminous flux per unit area
v	Speed (mm/s).
l	Length (mm).
t	Time (s).
T (%)	Transmittance in percentage for a specific wavelength.
A_f	Area of filament (mm²).
A_t	Total area (mm²).
$A_{60\%}$	60% of the profile area (mm²).
n	Number of glass fiber spools.
TEX	Nomenclature of Weight in grams per kilometer.

1. Object definition.

1.1. Purpose.

Learn about the UV curing process for composites and compare its advantages and disadvantages to the high-temperature mould curing method.

Adapt a conventional pultrusion line into a pultrusion line using UV light as the curing method for composites.

Evaluate its resource consumption in terms of material, energy, and time.

1.2. Finality.

The project's aim is to change the conventional curing mold of a pultrusion line. This mold must be capable of curing UV light composite with rectangular profiles of 20mm width and a thickness ranging from 1 to 4mm. Subsequently, an evaluation of the results will be conducted, and a proposal to upscale the prototype will be made.

1.3. Object.

The field of composite profile pultrusion is vast, and various universities and research centres have begun studying and producing different pultrusion lines that cure composites using UV light. This method offers some advantages over conventional methods, notably reducing the required time and energy consumption.

1.4. Context in the research and knowledge transfer lines of TecnoCampus.

The field of low-density composite materials is continuously advancing as the engineering industry looks for greater efficiencies in both components and manufacturing processes.

In this case the project is related to develop a new manufacturing method for PRFV. It is a research project that is currently in progress at only a limited number of universities worldwide, given its recent emergence. At TecnoCampus, this is the inaugural initiative exploring UV light-cured composites, which holds potential benefits for future undertakings in this field and offers a transfer of knowledge to interested students.

1.5. Gender perspective.

The integration of a UV source for light-based curing of continuous fibre composites in the pultrusion process is advantageous for gender inclusion, as it addresses the physical demands traditionally associated with this manufacturing method. The previous molds used in thermal curing were significantly heavy, posing a barrier for individuals who may not have the physical strength to handle them easily. With the new UV curing method, the weight of the molds can be reduced by at least five times, making them much lighter and easier to manage. This reduction in mold weight not only enhances workplace safety and ergonomics but also broadens the accessibility of these roles to all genders.

1.6. SGD (Sustainable Devolopment Goals).

The integration of a UV source for light-based curing of continuous fibre composites in the pultrusion process aligns with several Sustainable Development Goals (SDGs) by promoting innovative and sustainable manufacturing practices. Specifically, this technology can enhance SDG 9 (Industry, Innovation, and Infrastructure) by fostering advancements in manufacturing technologies that increase efficiency and product quality. The energy efficiency of UV curing also supports SDG 7 (Affordable and Clean Energy) by potentially reducing energy consumption compared to traditional thermal curing methods. Additionally, the development of high-performance composite materials can contribute to SDG 12 (Responsible Consumption and Production) by enabling the production of durable and lightweight components, which reduce material waste and extend the lifespan of products. Furthermore, the environmental benefits of reducing VOC emissions during the curing process support SDG 13 (Climate Action) by minimizing the ecological footprint of manufacturing processes.

2. Background and information needs.

2.1. Introduction to composite materials.

A composite material comprises at least two materials with differing properties.

There are two essential components in a composite material: the matrix and the reinforcement. The matrix, similar to a binder, holds the reinforcement material together and provides structural integrity. In the case of glass fibre, for example, the matrix is usually a resin that binds the glass fibres together. The term 'matrix' alludes to its role in encapsulating and supporting the reinforcement. Conversely, the reinforcement, such as steel reinforcing bars in reinforced concrete, gives the composite strength and specific properties.

Utilizing composite materials instead of traditional ones for components offers significant advantages, with weight reduction being a primary motivation. Additionally, composites excel in terms of thermal and chemical resistance, along with their exceptional electrical insulation properties. Unlike conventional materials, composites can combine various attributes rarely present in a single substance.

Fiber-reinforced composites, like PRFV, are gaining popularity in the development and production of end products for commercial purposes. This composite is the one which is going to be used for the project.

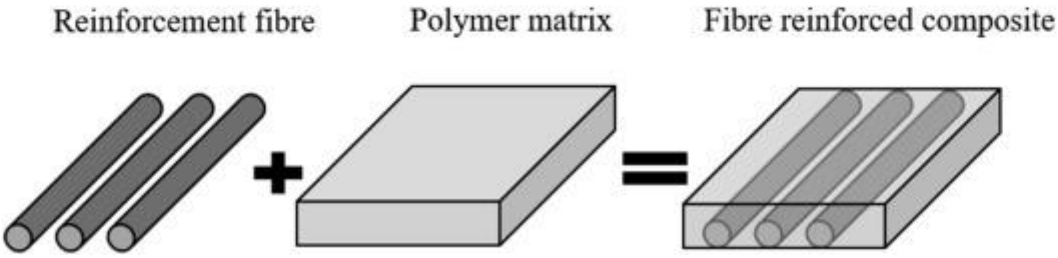

Fig. 2.1 Composite Material.

Source: [1]

2.2. Pultrusion Process.

Pultrusion is a continuous and automatic process for producing a constant cross-section. The term is an acronym combining "pull" and "extrusion". Unlike extrusion, in the pultrusion method the material is drawn.

This manufacturing process is very interesting because it is in continuous evolution and above all because the characteristics of the parts obtained by this process are very interesting.

This process is characterised by having a high percentage of glass fibre in comparison with other composite manufacturing processes, normally the percentage is approximately 60-65% glass fibre and 40-35% resin.

This composition offers a very light weight, being 2/3 the weight of aluminium and 1/4 the weight of steel. This translates into a higher stress/weight ratio than the two previous ones.

History JH Watson filed a very early patent for pultrusion in 1944. This was followed by MJ Meek's application in 1950. The first commercial pultrusion lines were supplied by the Glastic Company of Cleveland, Ohio under a patent filed by Rodger B. White in 1952. The patent granted to WB Goldsworthy in 1959 helped initiate the promotion and dissemination of knowledge within the industry. W. Brandt Goldsworthy is widely regarded as the inventor of pultrusion. [2]

2.2.1. Conventional pultrusion process.

Pultrusion is a continuous process used to manufacture fiber-reinforced polymer (FRP) composite profiles with a constant cross section having significantly long length.

This process is normally made using the next Conventional pultrusion line:

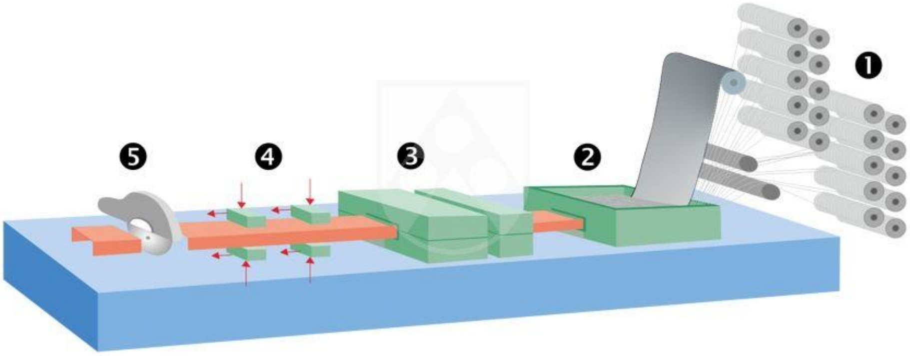

Fig. 2.2 Conventional pultrusion line.

Source: [3]

This streamlined process typically involves five distinct phases, each of which plays an integral role in the seamless execution of pultrusion:

1. **Unidirectional Spool Fibre Warehouse:**

The process begins with a unidirectional spool fibre warehouse, a raw material hub where the reinforcing fibres are located. These fibres, arranged in a single direction, serve as the basic building blocks for the following stages.

2. **Resin bath:**

The reinforcing fibres are then placed in a resin bath where they are delicately impregnated with resin. The purpose of this stage is to provide the fibres with the essential binder and to set the stage for subsequent moulding.

3. Preforming mould and heating mould:

The next stage is the preforming mould, which acts as a compact moulding tool. Designed to accurately define the profile, it also serves to remove any excess resin, ensuring a precise and optimum resin-to-fibre ratio. This is complemented by the heating mould, which is approximately one metre in length. This component plays a crucial role in the curing process, locking in the desired structure and properties. However, it's important to recognise that the heater mould has its own set of challenges. In particular, the disadvantages include.

- High cost: The manufacture of this mould and the energy consumption involved contribute to its high cost.
- Potential blockages: Due to its extended length, the mould can become clogged with resin flow, requiring careful management.

4. Pulling section:

The next stage in the process is the extrusion section. In conventional setups, these lines require a significant up-front investment in equipment. This is due to the need to counteract the high tensile forces involved, typically between 5 kN and 20 kN. These forces are essential to ensure the continuous movement of the material through the various stages.

5. Cutting section:

Finally, the cutting section completes the process. This is where the pultruded profiles are precisely cut to the required lengths, ready to be integrated into a wide range of applications. This step underlines the tailor-made nature of pultrusion, as profiles of different lengths can be produced according to specific requirements.

2.2.2. UV Curing Pultrusion line.

The UV pultrusion process offers a compelling alternative that avoids the need for the bulky heating moulds common to conventional lines and addresses the shortcomings associated with this established approach.

While the basic operation of the line remains the same, the difference lies in the curing process - a key departure that brings a host of benefits. By eliminating the traditional curing mould and introducing UV light as a replacement, this innovative method achieves a double transformation. Not only does it circumvent the challenges posed by conventional heated moulds, but it also opens the door to a realm of new possibilities, including the extrusion of curved profiles, a feat unattainable with the standard flat profile approach.

In essence, UV pultrusion redefines the manufacturing landscape by combining precision with efficiency. Through its inventive departure from tradition, it demonstrates the power of adaptability and creative problem solving and makes progress towards a more versatile and agile composite manufacturing methodology.

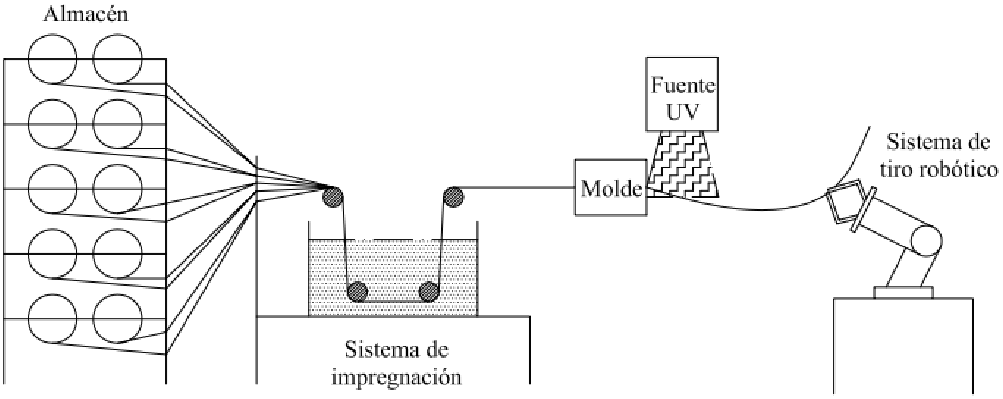

Fig. 2.3 Idea of the UV curing pultrusion line.

Source: [4]

1. **Unidirectional spool fibre storage:**

As with conventional methods, the process begins with a unidirectional spool fibre store. This raw material store holds the basic reinforcing fibres and sets the stage for the following stages.

2. **Resin bath:**

Similar to the conventional approach, the reinforcing fibres pass through a resin bath, a critical step where they undergo a meticulous infusion of resin. This infusion is critical to ensuring the structural integrity of the composite.

3. **Preforming mould:**

Entering a new dimension is the preforming mould, which spans a compact length of approximately 100mm. This mould plays a vital role in shaping the precursor profile, setting the stage for the innovative UV curing phase**.**

4. **UV light curing:**

A revolutionary departure from convention is seen in the UV light curing phase. Spanning a range of approximately 100 nm to 400 nm, with UV-A light in the optimal range of 320 nm to 400 nm, this method offers a spectrum of benefits that are reshaping the composite manufacturing landscape:

Benefits:

- Reduced curing time: The accelerated curing process translates into increased efficiency and productivity.
- Elimination of gel state: The absence of a gel state speeds up production and enables a seamless transition from mold to finished product.
- Reduced VOC emissions: Reduced volatile organic compound emissions contribute to a greener and more environmentally conscious production process.
- Extended shelf life: The shelf life of the composite is extended, providing operational flexibility.
- Reduced energy consumption: Reduced energy requirements underline the efficiency of the process.
- Increased safety: The uncomplicated containment process not only ensures simplicity, but also increases workplace safety.
- Simplified equipment: The cost-effective approach of the process is consistent with simplified equipment requirements.

Disadvantages:

- Limited Thickness for Curing: Curing can only occur within a small range of 8 to 13 millimetres.
- Requirement for Transparency: The materials used must be UV transparent and cannot include carbon or basalt reinforcements.
- Potential for Overexposure: Care must be taken to avoid overexposure, as it could harm the composite.

5. Pulling section:

For flat profiles that are 2 millimetres thick, an extrusion velocity of up to 2 metres per minute can be achieved. Using just 80 N of force will produce an extrusion velocity of roughly 0.65 m/min. This step showcases the process's great potential.

6. Cutting section:

The cutting stage is responsible for shaping the pultruded profiles to their desired lengths, closing the production cycle as it traditionally does.

2.2.3. Pultrusion line located in ILK.

Fig. 2.4 Pultrusion line of the ILK located in PEZ.

Source: Own Elaboration.

1. Spool fibre storage:

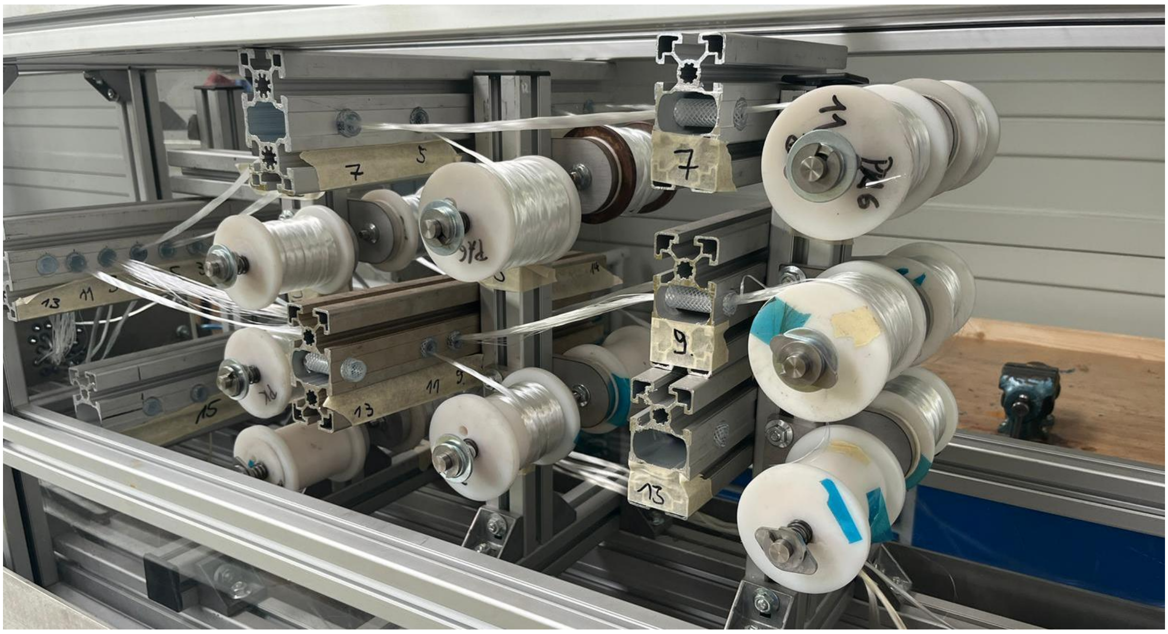

Fig. 2.5 Spool fibre storage.

Source: Own Elaboration.

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2. Resin bath:

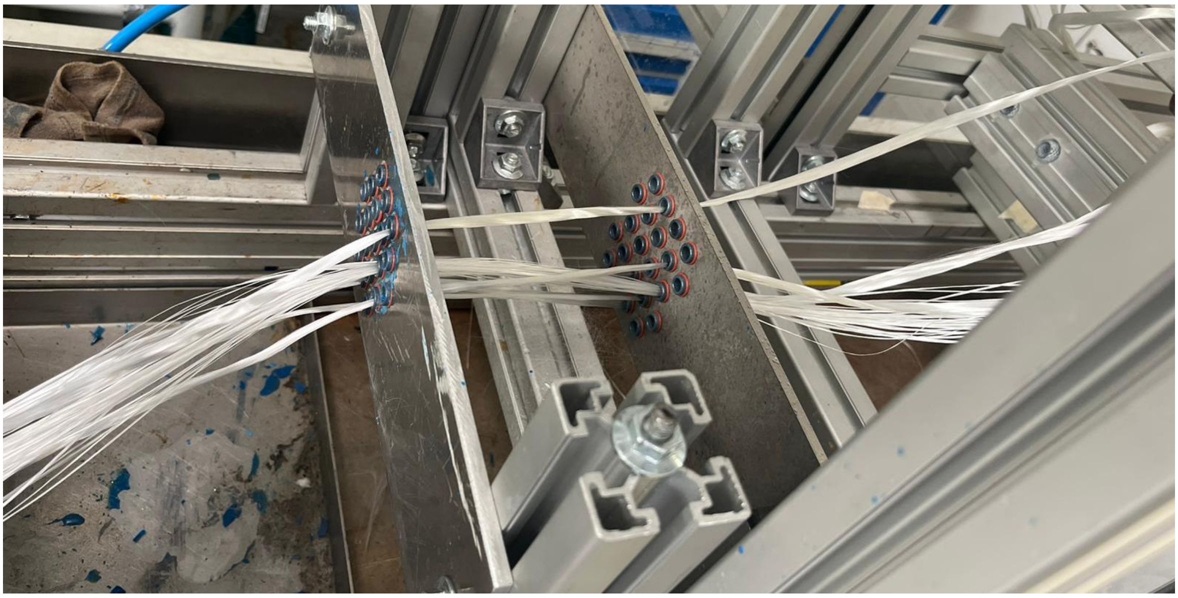


Fig. 2.6 Location of the resin bath.

Source: Own Elaboration.

3. Mold section:

Fig. 2.7 Location where is going to be the designed mold.

Source: Own Elaboration.

4. Pulling section:

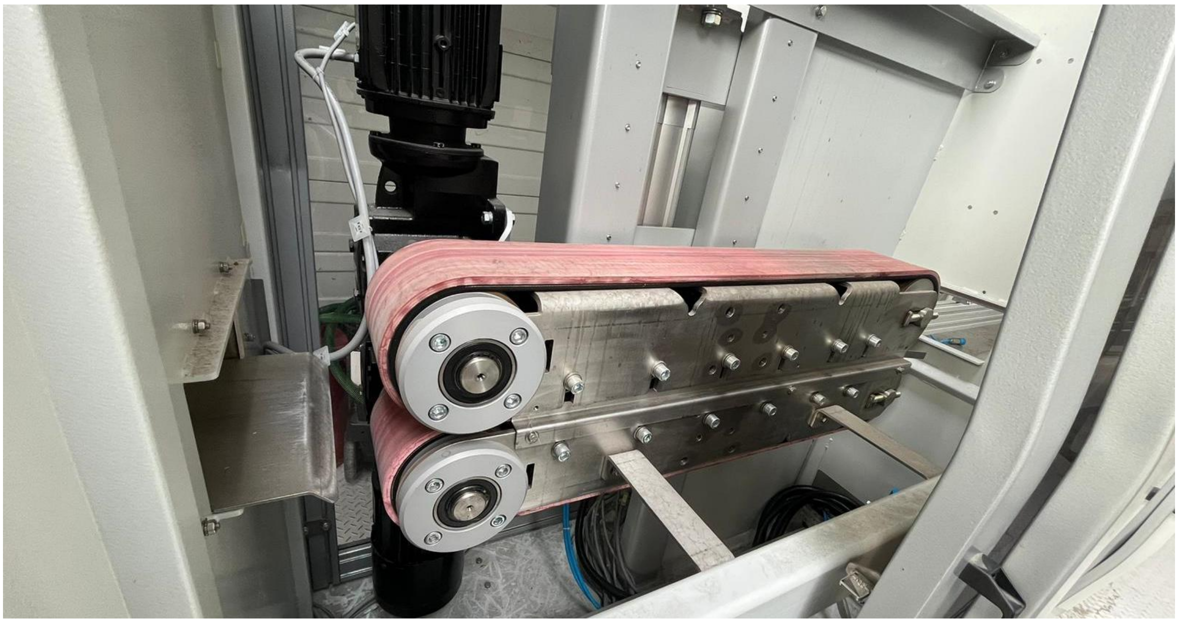


Fig. 2.8 Pulling machine.

Source: Own Elaboration.

5. Cutting section:

Fig. 2.9 Cutting machine.

Source: Own Elaboration.

2.3. Photopolymerization process.

The use of photoinitiated polymerization is rapidly increasing in various industries, as demonstrated by its wide applications in coatings, inks, adhesives and cutting-edge areas such as optoelectronics and nanotechnology. This perspective examines the latest developments in initiation systems for radical and cationic polymerisations. It also highlights the possibility of using photochemical techniques for step-growth polymerization, addressing issues related to efficiency, wavelength adaptability and environmental safety. Advances in the last ten years concern the production of complicated macromolecules by photoinitiated polymerisations, which have promising future prospects in fields such as biomaterials, surface alteration, copolymer synthesis and nanocomposites.

For the curing process of composites, the photopolymerization process, a UV curing method that exploits the use of free radicals, is starting to be used. This process can be dissected into three distinct phases:

- **Initiation Stage:** At the onset, the photoinitiator assumes the pivotal role of catalyzing the reaction. It adeptly converts the radiant energy from UV light into chemical energy, thereby instigating the formation of free radicals.
- **Propagation Stage:** Progressing into the propagation phase, these newly formed free radicals engage with the monomers. The result is the construction of a polymeric chain, a phenomenon akin to what is observed in thermal curing methods.
- **Finishing Stage:** Culminating in the finishing phase, the polymer undergoes crosslinking. This can be achieved through a bimolecular reaction between free radicals (coupling). Alternatively, crosslinking may occur via the transfer of atoms between different chains (disproportion).

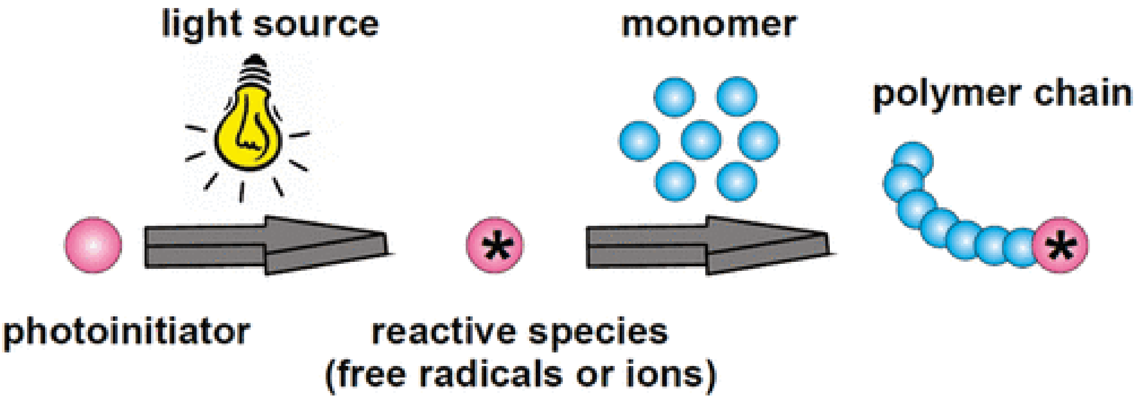


Fig. 2.10 Scheme of Photoinitiated Polymerization.

Source: [5]

For the execution of this process, a UV LED light source is conventionally employed. This source emits UV light within the wavelength range of 320 nm to 400 nm, optimally suiting the photopolymerization requirements.

2.3.1. UV curing resin.

This type of resin is a little bit different than the normal resins used in the pultrusion line. These resins are composed by the next following components. [6]

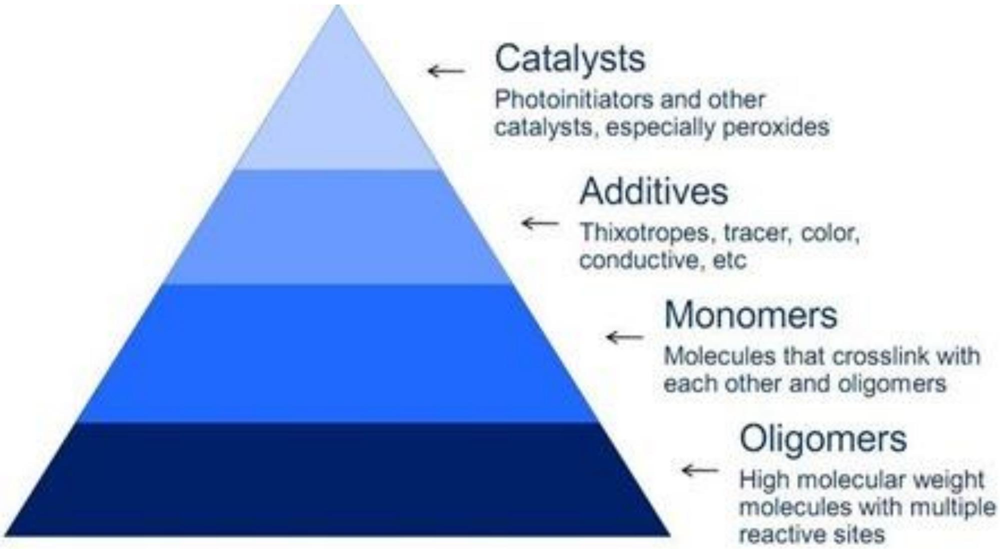


Fig. 2.11 Components of the UV resins.

Source: [7]

1. **Base Resin (Oligomers and Monomers):** Epoxy acrylate resins, which are thermoset resins, make up the primary portion of the UV resin. These resins provide the fundamental properties of the material.
2. **Catalysts (Photoinitiators):** Photoinitiators are crucial in the UV curing process, as they initiate polymerization when exposed to UV light. In the UV pultrusion process, UV LED lights with a wavelength range of about 320 nm to 400 nm (UV-A range) are commonly used.

   Common photoinitiators include:

   - MAPO (Mono acyl phosphine oxide) with UV absorption at 395 nm.
   - BAPO (Bis acyl phosphine oxide) with UV absorption at 395 nm.
   - BEE (Benzoin ethyl ether).
   - α-aminoketone with UV absorption at 320 nm and some absorption at 400 nm.

   It's noted that these photoinitiators can be combined, with the combination of BAPO photoinitiators (1.2%) and α-aminoketone (0.4%) being particularly suitable for the UV pultrusion process. [4]

3. Commercial Names of Photoinitiators:

- BAPO is commercially known as Irgacure 819.
- α-aminoketone is commercially known as Irgacure 379.

3. Scope of the project.

Yes:

- Information about the Pultrusion process.
- Information about previous studies referring to the UV curing pultrusion method.
- Find and understand a mathematic model to know the curing time of the composite.
- Design and manufacture the prototype mold for the UV pultrusion line.
- Experiments with the manufactured mould.
- Analysis of the results of experiments.
- Conclusions about the results and proposing different parameters to improve the process and purpose different type of molds.
- Design a final process and mold using the conclusions of the first prototype.
- Budget for the project.

No:

- Characterize the resin by experiments.
- Use the mathematic UV Curing model.
- Manufacture and experiment with the final prototype.

4. Targets and technical specifications.

- **Target 1:** Understand the UV Pultrusion Process and Photopolymerization.

Technical specifications:

- Describe the pultrusion process and explain its purpose.
- Explain the mechanics of the UV pultrusion process.
- Clarify the concept of photopolymerization and explain its mechanism.
- Explain the applications and advantages of the UV pultrusion process.

- **Target 2:** Design and manufacture a mold prototype.

Technical specifications:

- Using all the information gathered from other studies, define the necessary mold measurements.
- Find the materials required for the mould while minimizing costs as much as possible and utilizing the 3D printer to its fullest potential.
- Outline the initial concept, identify any issues, resolve them, and refine the design until the optimal solution is reached.
- Manufacture the mold and install it onto the pultrusion line.

- **Target 3:** Design the process and do some experiments.

Technical specifications:

- Research previous studies to determine the curing time of the composite and make an initial approximation of the extrusion speed.
- Conduct experiments on the pultrusion line, varying the extrusion speed and force.

- **Target 4:** Design a final mold prototype.

Technical specifications:

- Design a new 3D prototype, using all the information gathered from the experiments with the first prototype.
- The new prototype must be adaptable to pultrude different thickness between 1mm and 4mm of the rectangular shape.
- Explain how to adapt the mold to the pultrusion line and how to use it (UV light parameters and pultrusion speed)
- Calculate the resource consumption in terms of material, energy, and time.
- Make a budget for the complete installation.

5. Generating and proposing alternative solutions.

5.1. Introduction.

The application of ultraviolet (UV) light curing pultrusion technology represents a significant evolution in the field of mechanical engineering, particularly in the conventional pultrusion process. In this innovative method, the aim is to preserve the essence of the traditional pultrusion process, but with a crucial modification: replacing the curing section, previously carried out through the application of temperature and pressure, with a UV light-driven curing section.

In this context, two different implementation variants are proposed to address the solution to this advanced technology.

1. **UV Curing after a preforming mold.**

UV curing after a preform mold is a crucial step in the prototyping process used by Ivan and Tena in their doctoral thesis [4]. This method is based on a preform mold of the profile through which the fibers and resin pass in their natural state. Once the composite comes out of the preform mold, it is exposed to UV light for the curing process.

The use of UV curing has shown satisfactory results in terms of achieving the desired curing properties. However, it is important to note that, because curing takes place immediately out of the mold, the profile of the composite tends to show some irregularities. This tendency of the profile to expand as it exits the mold introduces challenges in maintaining dimensional accuracy and requires careful consideration in the overall design and process control.

The sketch of this Idea is shown in [Fig. 2.3 Idea of the UV curing pultrusion line.]

2. UV Curing inside the mold.

UV curing within the mold, despite its potential to address irregularities in the pultruded profile associated with the curing process after the preform mold, has not been the subject of current studies. This approach emerges as an intriguing study option, as it offers the possibility of overcoming challenges inherent in the deformities observed in the previous process.

In this method, UV curing takes place while the composite is still within the mold, allowing for more precise control over the formation and setting of the structure. This variant has the potential to mitigate irregularities arising from profile stretching upon exiting the mold, providing an opportunity to obtain pultruded profiles with more accurate and uniform dimensions.

The lack of recent studies underscores the importance of thoroughly investigating this technique, evaluating its advantages and potential challenges. It would be beneficial to explore specific UV curing parameters, exposure times, and mold conditions to optimize the quality of the final product.

The main challenge of this process lies in achieving a mold design adaptable to the pultrusion line and incorporates suitable materials to allow UV light to irradiate the composite.

6. Solution development.

6.1. Introduction.

The task at hand pertains to the creation of a mold designed to pultrude a rectangular profile measuring 20mm x 2mm.

After careful evaluation of the advantages and disadvantages of the two previous proposals, the decision has been taken to opt for UV curing inside the mold. Although no specific studies exist as a guide, it is considered that this choice could represent the solution to the problem of irregularity observed in the last studies. This decision is based on the prospect of achieving greater dimensional accuracy and improved uniformity in the curing of the composite.

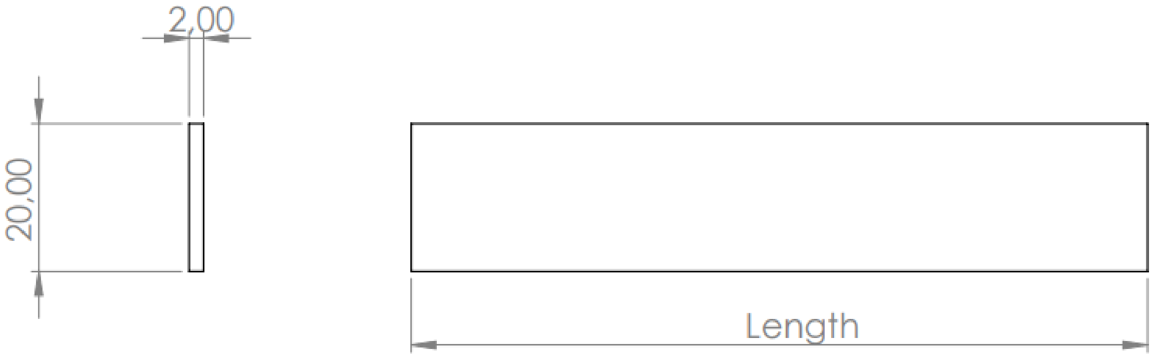


Fig. 6.1 Sketch of the pultruded profile (mm).

Source: Own Elaboration.

The new mold shall replace the curing element in the conventional pultrusion line present within the facility. Consequently, adapting the mold's dimensions to suit the line is essential.

6.2. Mold design.

6.2.1. Materials.

The selected printer is the BambuLab X1 Carbon with a print size of 256 x 256 x 256 mm^3, which is sufficient for all mold components. This printer can print many materials, including common ones like PLA, PETG, and ABS and less common ones like PA-CF. [8]

PROPERTIES	PLA	ABS
Tensile strength	10 – 70 MPa	40 – 50 MPa
Elongation at break	1.5 – 380 %	15- 30 %
Modulus of elasticity	2500 – 4500 MPa	1900 – 2700 MPa
Flexural strength	55 -80 MPa	75 MPa
Flexural modulus	2500 – 4000 MPa	1700 -1900 MPa

Table 6.1 Properties about PLA and ABS 3D printed materials.

Source: [9]

In terms of mechanical properties, ABS is better because the elongation is lower and the range of other properties is lower, so ABS is more predictable under stress with similar properties.

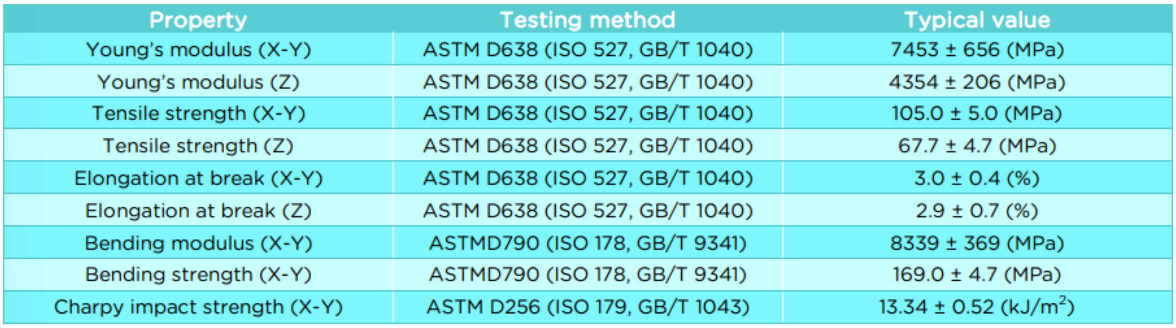
Apart from the mechanical properties, it is important to determine which material performs better when exposed to UV radiation, as our mold will be subjected to such light. In this case the better material is PLA compared to ABS. [10]

ABS 3D printed material can reach a tensile strength of 32 MPa, using a printing velocity of 50 mm/min.

In terms of UV light resistance, the best material is ASA, this material has similar mechanical properties as ABS and is characterized by high resistance to a wide range of oils and greases and resistance to high temperatures. [11]

An alternative material is PA6-CF, this material is made by a mix of PA and 20% of the weight of carbon fiber. Apart from the UV resistance, the mechanical properties are also better than those of common materials.

The following table is about the mechanical properties of the PA6-CF with a nozzle temperature of 300ºC, printing speed of 45mm/s, shell of 0.8mm and an infill of 100%.



Property	Testing method	Typical value
Young's modulus (X-Y)	ASTM D638 (ISO 527, GB/T 1040)	7453 ± 656 (MPa)
Young's modulus (Z)	ASTM D638 (ISO 527, GB/T 1040)	4354 ± 206 (MPa)
Tensile strength (X-Y)	ASTM D638 (ISO 527, GB/T 1040)	105.0 ± 5.0 (MPa)
Tensile strength (Z)	ASTM D638 (ISO 527, GB/T 1040)	67.7 ± 4.7 (MPa)
Elongation at break (X-Y)	ASTM D638 (ISO 527, GB/T 1040)	3.0 ± 0.4 (%)
Elongation at break (Z)	ASTM D638 (ISO 527, GB/T 1040)	2.9 ± 0.7 (%)
Bending modulus (X-Y)	ASTMD790 (ISO 178, GB/T 9341)	8339 ± 369 (MPa)
Bending strength (X-Y)	ASTMD790 (ISO 178, GB/T 9341)	169.0 ± 4.7 (MPa)
Charpy impact strength (X-Y)	ASTM D256 (ISO 179, GB/T 1043)	13.34 ± 0.52 (kJ/m^2)

Table 6.2 Mechanical properties of PA6-CF.

Source: [12]

One issue associated with 3D printing is the creation of small threads; however, a compelling substitute is available in the form of thread inserts. Thread inserts are metallic elements, incorporated into 3D printed parts to provide a robust and durable threading solution. These inserts are placed into pre-designed holes in the printed piece, offering a metallic surface for bolts and screws.

The main reason for using thread inserts in 3D printed parts is because the printing process can result in layers of material that are sometimes less strong or durable compared to metal. By using thread inserts, the strength and reliability of metal are leveraged for threaded connections, preventing issues.

For the design, it is necessary to decide which size of insert to use and to make a hole in the design with the dimensions indicated in the manufacturer's tables. This ensures a proper fit and optimal performance of the thread insert in the 3D printed part.

The model of the inserts is the M6 Threaded Insert.

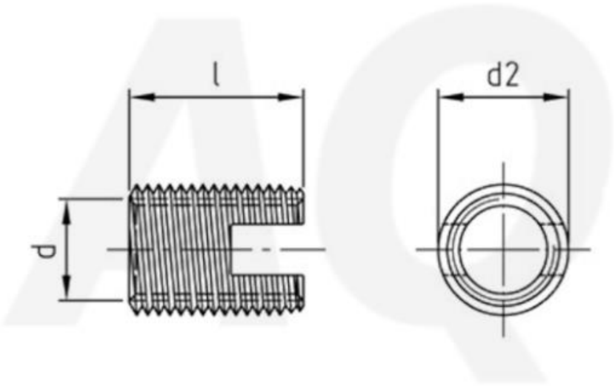
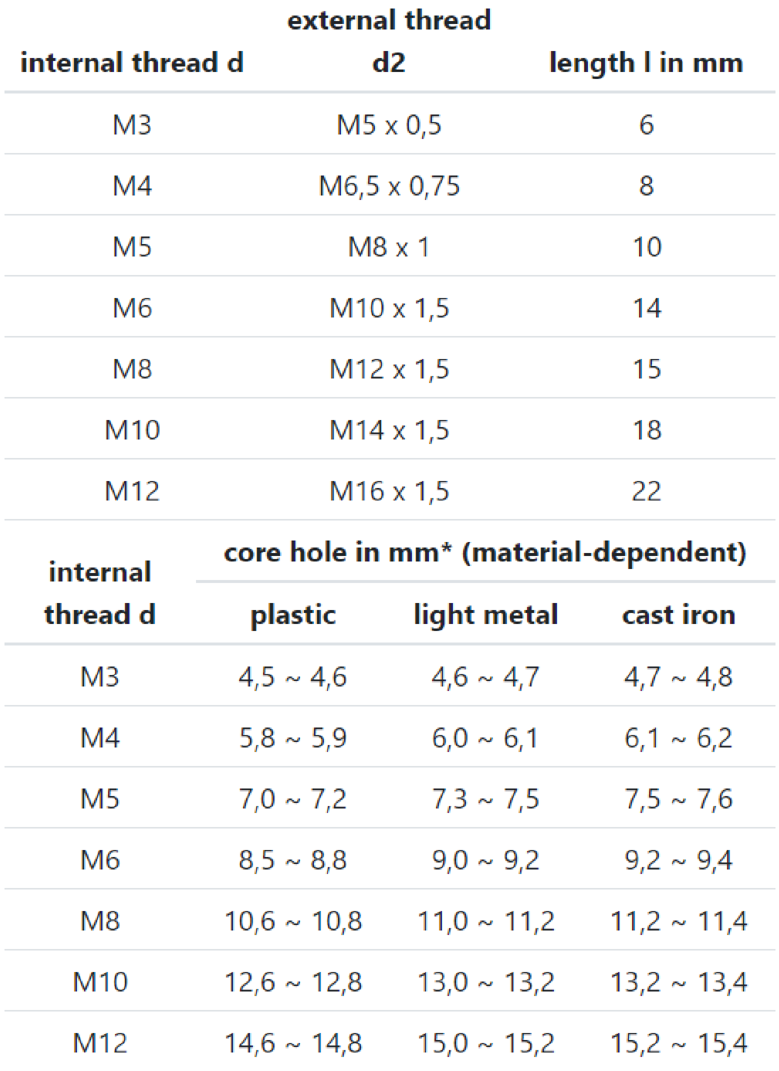


Fig. 6.2 M6 Thread Insert sketch.



internal thread d	external thread d2	length l in mm
M3	M5 x 0,5	6
M4	M6,5 x 0,75	8
M5	M8 x 1	10
M6	M10 x 1,5	14
M8	M12 x 1,5	15
M10	M14 x 1,5	18
M12	M16 x 1,5	22

internal thread d	core hole in mm* (material-dependent)		
	plastic	light metal	cast iron
M3	4,5 ~ 4,6	4,6 ~ 4,7	4,7 ~ 4,8
M4	5,8 ~ 5,9	6,0 ~ 6,1	6,1 ~ 6,2
M5	7,0 ~ 7,2	7,3 ~ 7,5	7,5 ~ 7,6
M6	8,5 ~ 8,8	9,0 ~ 9,2	9,2 ~ 9,4
M8	10,6 ~ 10,8	11,0 ~ 11,2	11,2 ~ 11,4
M10	12,6 ~ 12,8	13,0 ~ 13,2	13,2 ~ 13,4
M12	14,6 ~ 14,8	15,0 ~ 15,2	15,2 ~ 15,4

Table 6.3Diameter of the holes for thread inserts.

Materials able to use in the range of UV-A wavelength.

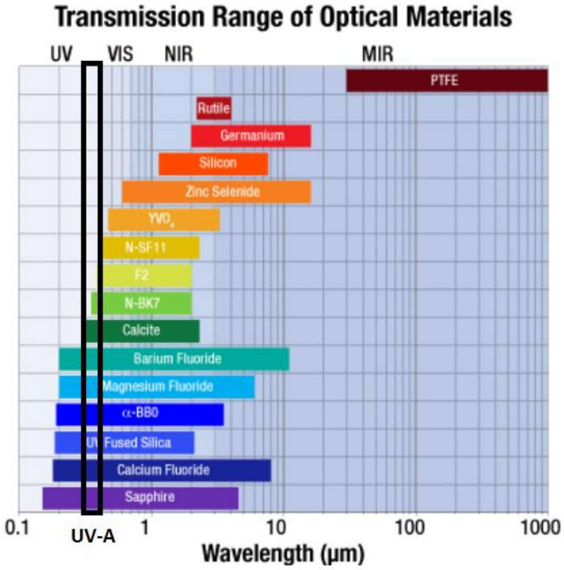


Fig. 6.3 Chart of Transmission range of different materials - Wavelength (nm).

Source: [13]

There are various materials that can transmit light in the UV-A wavelength range. The graph depicted below displays the transmission capacity of different materials at various wavelengths. However, the graph doesn't reveal the transmission percentage or degree for each material at specific wavelengths. Hence, it is mandatory to individually evaluate the materials to determine the most favourable option for use.

To start with, different prototypes of the curing mold with the necessary features have been made until what seems to be the optimal solution was found. The first mold designed was basic, but it was so interesting to make clear the idea of how the mold works, the necessary length and the position of the UV lights. The mold is based on two side pieces where the Quartz glass plates are held. The total length of the mold is 120mm, this length is provided by the other thesis which states that the total length required for the mold in this process is approximately 100mm.

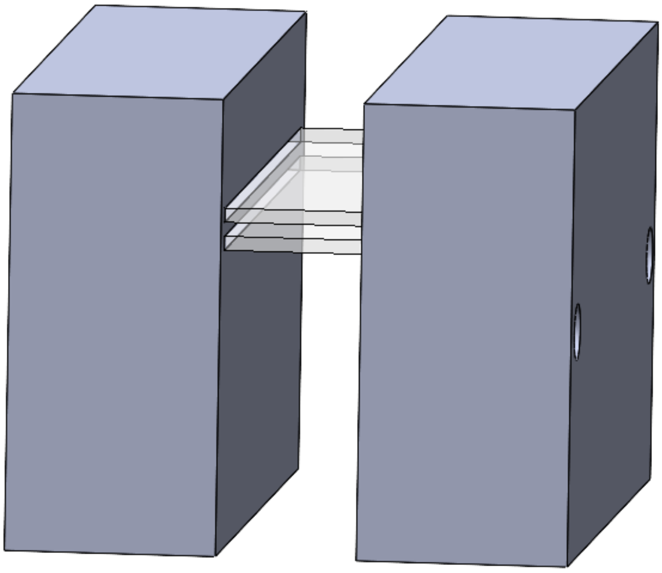


Fig. 6.4 First idea for the mold.

Source: Own elaboration.

The next step was developing the same idea in a real prototype taking in a count, the lamps, how these lamps are going to get hold in the mold and the real measures of the pultrusion line that we have in the institute.

The final prototype is designed to be flexible for varying thicknesses of rectangular profile shapes, ranging from 0.5mm to 4mm in thickness. The remarkable feature of this process is that modifying only two components of the mold is sufficient to alter the profile thickness. However, adjusting the profile width necessitates changing several other mold parts, including the inlet and outlet, as well as the quartz glass plates.

All the Blueprints are available in the respective document.

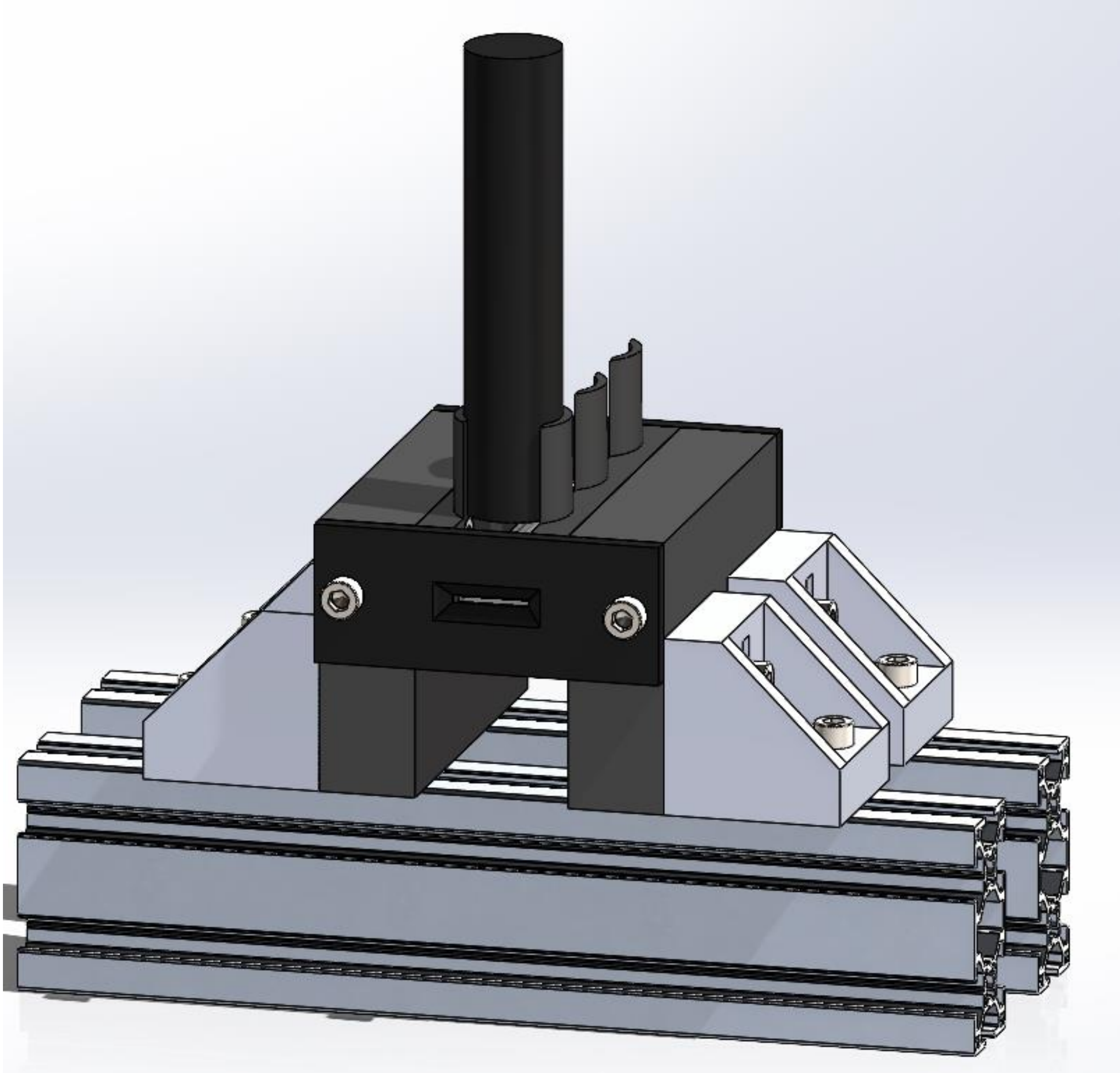


Fig. 6.5 Final prototype for the mold.

Source: Own elaboration.

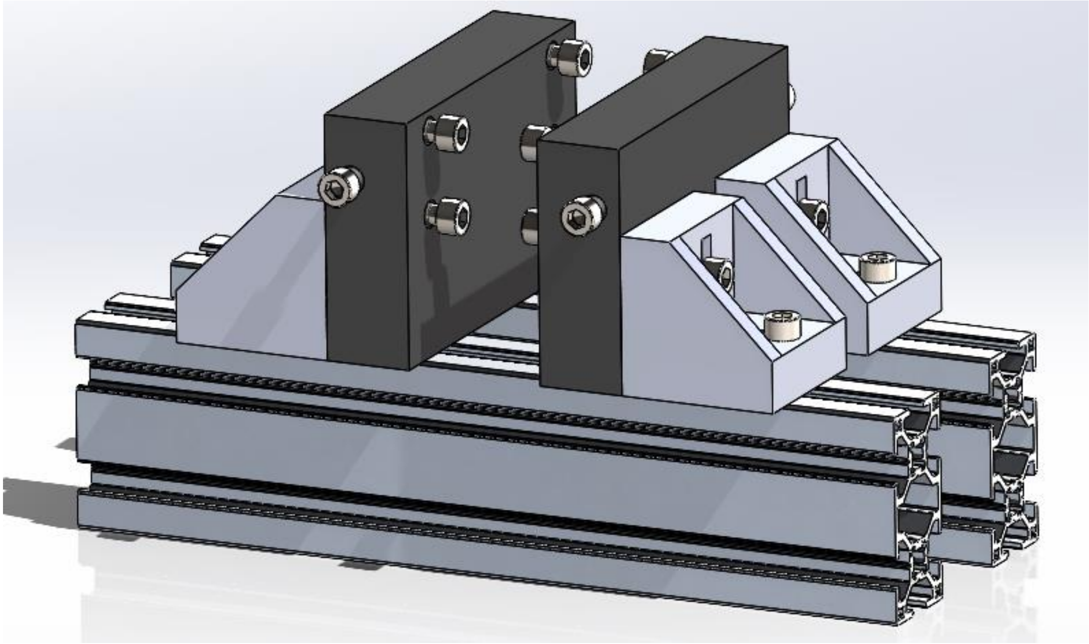


Fig. 6.6 Fixed parts for all rectangular shapes.

Source: Own elaboration.

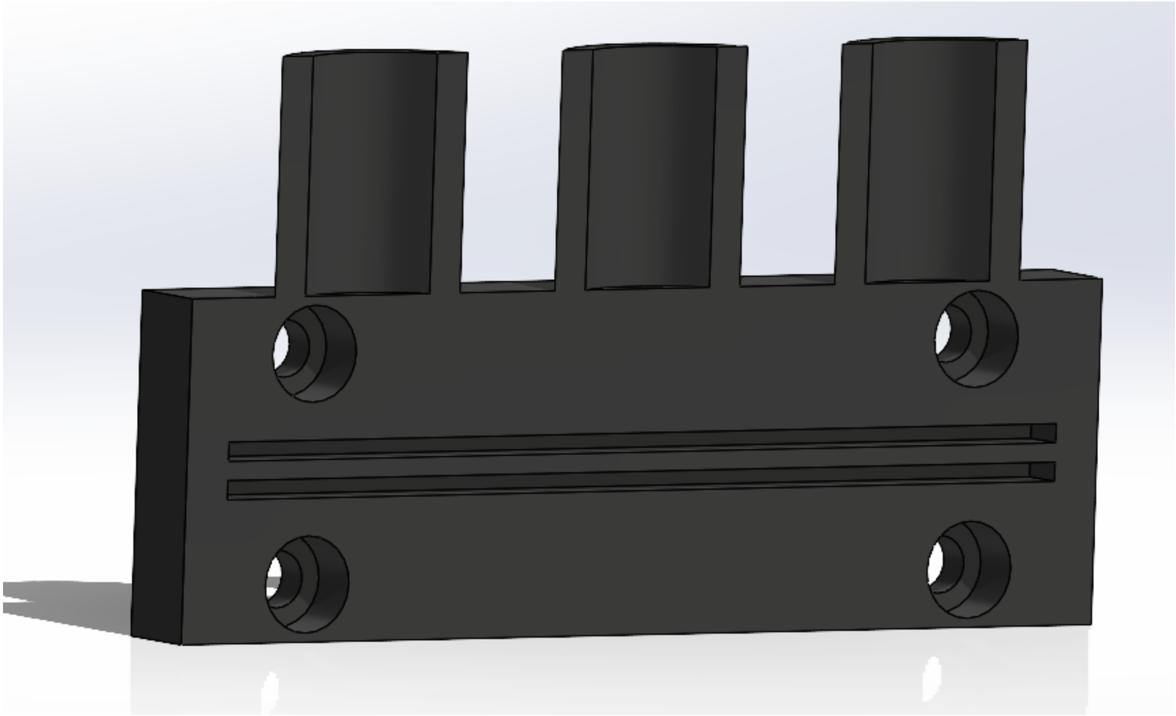


Fig. 6.7 Editable part to change the thickness.

Source: Own elaboration.

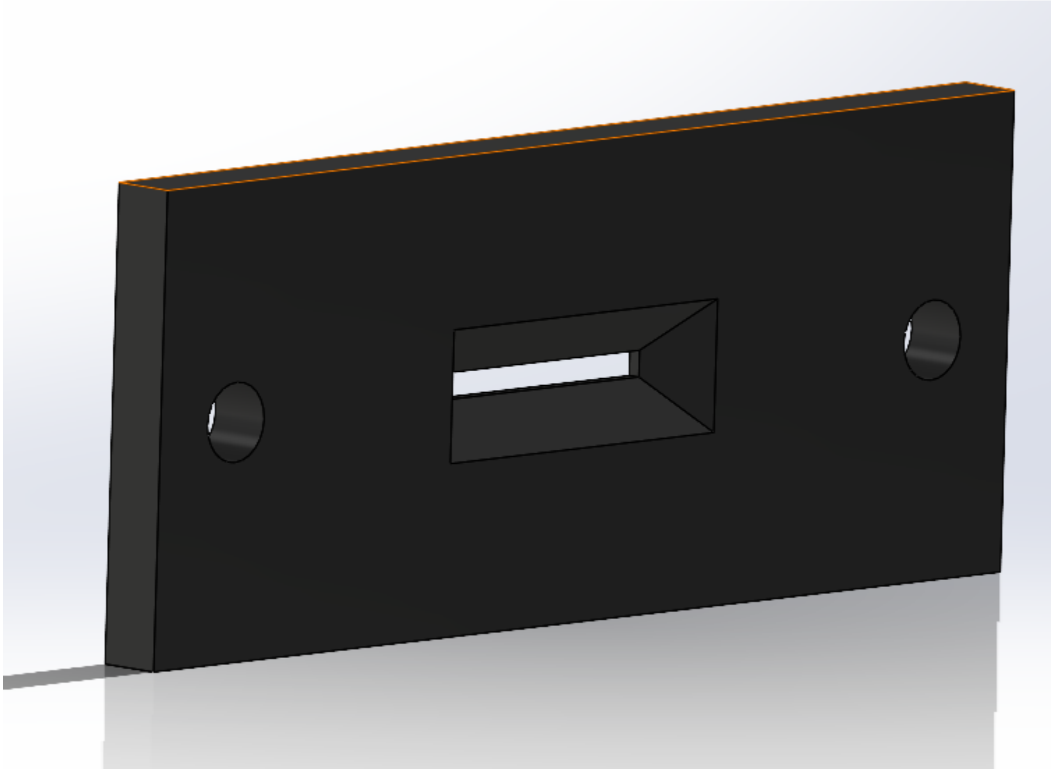


Fig. 6.8 Editable part to change the profile entrance.

Source: Own elaboration.

6.2.2. Manufacture of the first prototype.

In the manufacturing of the different parts of the mold, it is essential to define various printing parameters that will provide strength and functionality to our mold. These parameters include layer height, infill, print speed, and, in the case of parts that will have thread inserts, a wall thickness in those areas to ensure that the insert can thread properly since 100% infill is necessary in these areas the wall thickness needed is provided by the datasheet of the thread inserts in the table 6.3, under the section "core hole in mm," which depends on the chosen thread size. This ensures that the inserts are properly secured and function as intended.

All of this is done using Bambu Lab's slicer software. This software allows us to set the specific parameters for each part of the mold to ensure optimal strength and functionality. The slicer software is user-friendly and helps us precisely control the printing process, even if you are not familiar with 3D printing.

To explain how Bambu Lab's slicer software works, we will demonstrate all the steps and parameters used to print Part 1 of the mold.

Steps to Set Up and Print Part 1 of the Mold Using Bambu Lab Slicer

1. **Open the Bambu Lab Slicer Software:** Launch the Bambu Lab slicer software on computer.
2. **Load the 3D Model:** Import the 3D model of Part 1 of the mold into the slicer software, it’s important to say that the 3D Model must be a STL file.
3. **Then we start to set the printing parameters:** First, decide which material is going to be printed (that point is important because in BambuLab Slicer the settings of temperature of the nozzle and bed are set automatically with the material selection. Secondly, set the layer height to your desired specification, which determines the resolution of the print. A typical layer height is 0.2 mm, but this can be adjusted based on the required detail and strength.

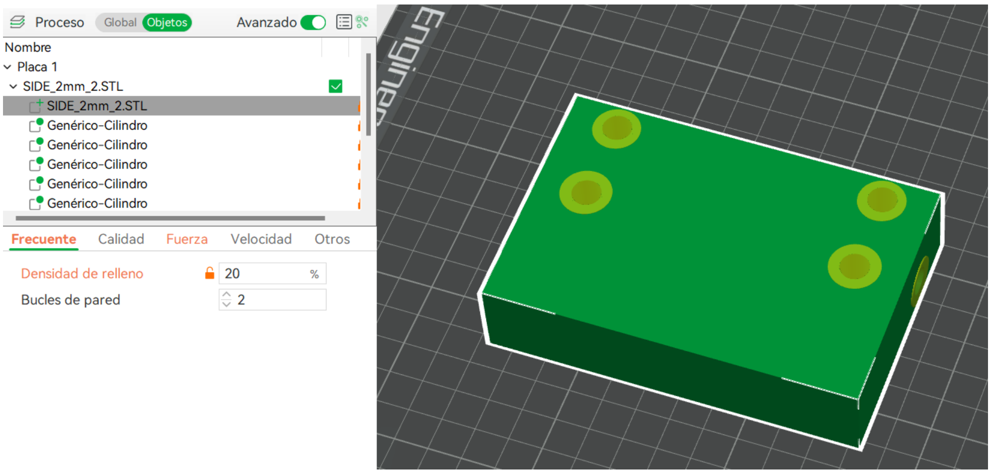
   Adjust Infill Density: In the same "Print Settings" tab, find the infill density setting. Set the infill to provide the necessary strength for the mold. Common infill settings range from 20% to 50%, but for parts with thread inserts, you may need to set specific areas to 100% infill.

Ancho de línea

Pared exterior	0,4 mm
Pared interior	0,4 mm
Superficie superior	0,4 mm
Relleno poco denso	0,4 mm
Relleno sólido interno	0,4 mm

Table 6.4. Wall layer thickness of BambuLab Slicer.

Source: Own elaboration.

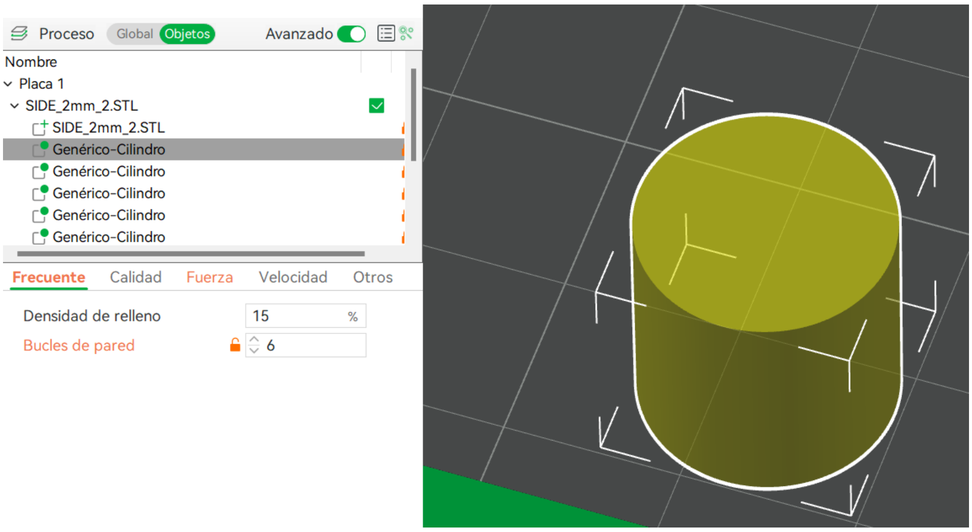


Densidad de relleno 20 %

Bucles de pared 2

Fig. 6.9 Wall layers and infill of the Part 1.

Source: Own elaboration.



Densidad de relleno 15 %

Bucles de pared 6

Fig. 6.10 Wall layers for the holes of thread inserts.

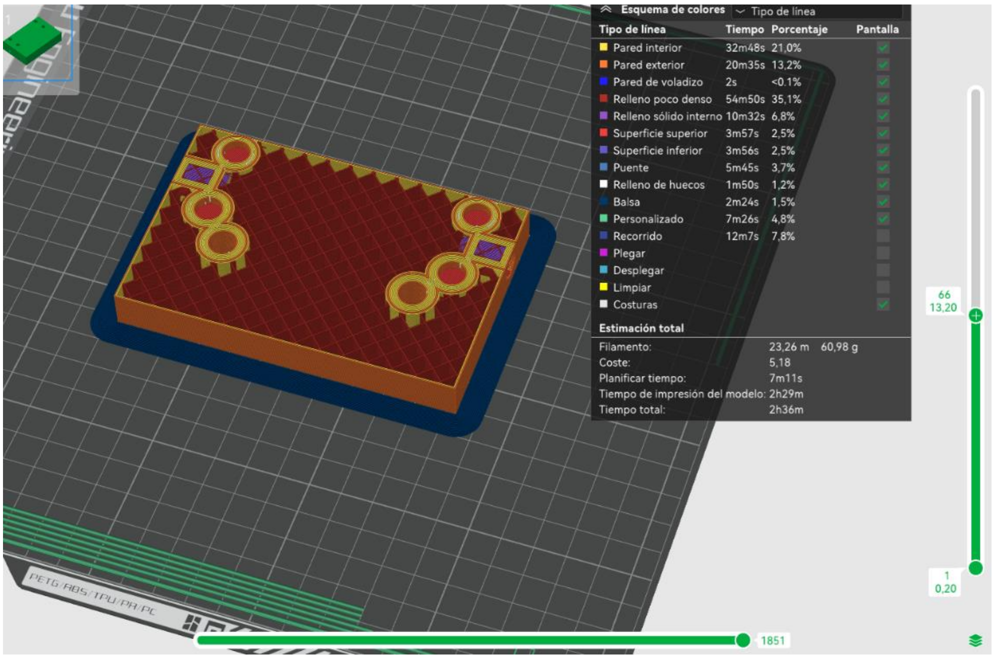
Source: Own elaboration.

As shown in the previous figures, in this case, I decided to print with 20% infill and a wall layer thickness of 0.4mm. The wall thickness will be 0.8mm, except in the holes designed for the thread inserts, where the walls will have a thickness of 2.4mm.

The core hole will be the diameter of the hole (Ø5mm) plus the wall thickness multiplied by 2 because the thickness is in radius. Therefore, the core hole will be 9.6mm. According to Table 6.3, we need at least a core hole in plastic of Ø8.8mm.

Finally, in the "Print Settings" tab, adjust the print speed. This can affect the quality and strength of the print. Typical print speeds range from 40 mm/s to 60 mm/s in the cheapest printers, The Bambu Lab X1 Carbon can print PLA at speeds up to 500 mm/s. However, for best results, it is generally recommended to print at speeds ranging from 60 mm/s to 150 mm/s depending on the complexity and size of the print. So, we will print at 150mm/s for the external walls and 200 mm/s for the internal infill to go faster.

4. **Preview the Print:** Use the preview function to visualize the layer-by-layer construction of Part 1. Ensure that all parameters are correctly applied, especially around the thread insert areas.



Tipo de línea	Tiempo	Porcentaje	Pantalla
🟨 Pared interior	32m48s	21,0%	✓
🟧 Pared exterior	20m35s	13,2%	✓
🟦 Pared de voladizo	2s	<0.1%	✓
🟥 Relleno poco denso	54m50s	35,1%	✓
🟪 Relleno sólido interno	10m32s	6,8%	✓
🟥 Superficie superior	3m57s	2,5%	✓
🟪 Superficie inferior	3m56s	2,5%	✓
🟦 Puente	5m45s	3,7%	✓
⬜ Relleno de huecos	1m50s	1,2%	✓
🔵 Balsa	2m24s	1,5%	✓
🟩 Personalizado	7m26s	4,8%	✓
🟦 Recorrido	12m7s	7,8%	☐
🟪 Plegar			☐
🟦 Desplegar			☐
🟨 Limpiar			☐
⬜ Costuras			✓

Estimación total

Filamento: 23,26 m 60,98 g
Coste: 5,18
Planificar tiempo: 7m11s
Tiempo de impresión del modelo: 2h29m
Tiempo total: 2h36m

Fig. 6.11 Preview of the process.

Source: Own elaboration.

5. **Generate G-code:** Once all settings are verified, generate the G-code file by clicking on "Slice" and then "Export G-code." And then transfer the G-code file to your 3D printer via SD card, USB, or direct connection.

   By following these steps, you can ensure that Part 1 of the mold is printed with the correct parameters, providing the necessary strength and functionality. The Bambu Lab slicer software simplifies this process by allowing precise control over each aspect of the print.

6.3. Curing process parameters.

Calculate extrusion speed of the pultrusion line:

To reach this step, it is essential to know the exposure time to the UV light source necessary to obtain complete curing of the desired composite.

Once the time has been obtained from the previous experiment or from the resin manufacturer's data, the exposure length is also needed to calculate the speed.

- v = speed (mm/s).
- l = length (mm).
- t = time (s).

Possible problems:

1. The UV curing time is experimented in a static situation and the UV curing process in a pultrusion line is dynamic and probably the times will be different.
2. Our light has a circle shape, this shape probably is going to cause problems because the extruded profile has a rectangular shape, and each part will have a different exposure time to UV light.

Possible solutions:

1. If the time doesn’t fit and the samples are not curing in a good way, experiment in the pultrusion line, with different speeds.
2. Try to use a UV light with a rectangular shape with more than 20 mm width, the length is not important to achieve a better curing degree but the longer the flashlight the higher the speed at which it can be extruded as there is more area of exposure.

6.3.1. Experiments outside the mold.

The first step is to check that the curing times provided by other experiments in the Composite UV Light Printer are correct. After checking the curing time, the next challenge is to see if the composite sticks to the mold after the curing process, and to think and experiment about how not to get stuck.

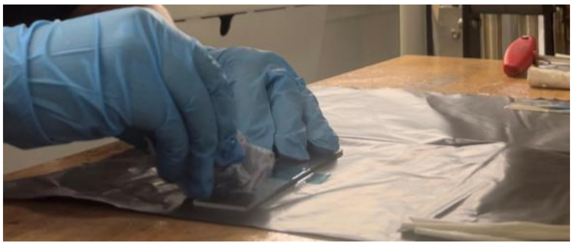
Fig. 6.12 Material for the first experiment.

Source: Own elaboration.

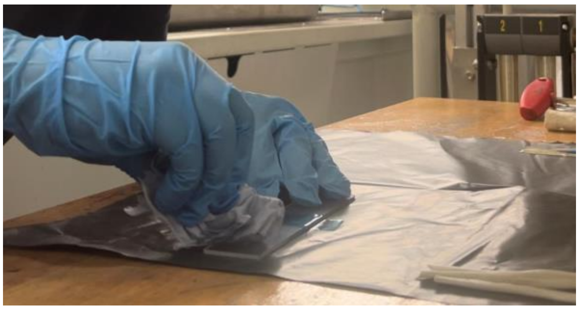
- For these experiments the material need is:
    - Resin: Raylock C1101 (15g - 20g).
    - Quartz Glass Plate.
    - UV flashlight (365nm).
    - Release Agent (Loctite 770-NC).
    - Glass Fiber 4800 TEX.
    - Protection Glasses.
    - Protection Gloves.
    - Scissors.
    - Acetone.
    - Paper.

Procedure for Conducting Experiments:

- **Initial Cleaning:** Begin each experiment by thoroughly cleaning a Quartz Glass plate with acetone. Ensure that the plate is free from any contaminants or residues.

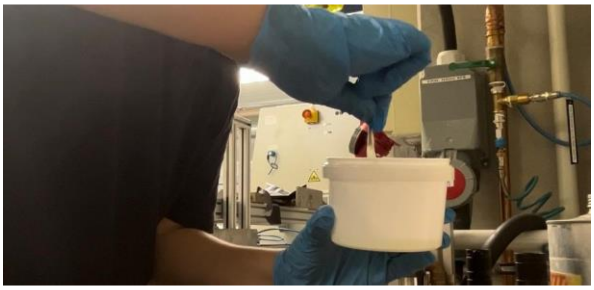


- **Release agent application:** Once the Quartz Glass plate is cleaned, apply the release agent 770-NC with a wet paper in the Quartz Glass plate. Then wait 5 minutes for curing and start with the next step.

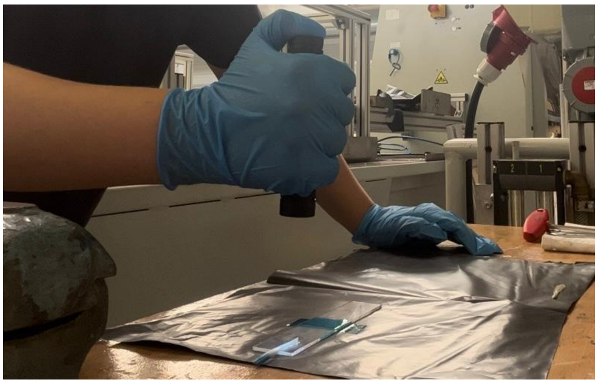


- **Sample Preparation:** Prepare samples of glass fiber measuring 50 mm in length. These samples should be cut from the 4800 TEX roving material.

- **Resin Application:** Take one of the glass fiber samples and apply a suitable amount of resin. Ensure that excess resin is carefully removed to maintain precision. Once adequately wetted with resin, place the sample onto the prepared Quartz Glass plate.



- **Curing Process:** Initiate the curing process by exposing the composite to UV light from a flashlight. Record the exposure time for each experiment to determine the optimal curing duration. Repeat this step as needed to assess various curing times.



- **Demolding and Evaluation:** Upon completion of the curing process, carefully demold the composite from the Quartz Glass plate. Inspect the composite to determine whether it adheres to the plate or not. If it sticks, consider applying a suitable release agent as necessary.

Results of experiments:

Once the time has been obtained from the previous experiment or from the resin manufacturer's data, the exposure length is also needed to calculate the speed.

$$v = \frac{l}{t}$$

Where:

“v” represents the speed.

“l” denotes the length of the cured material.

“t” signifies the curing time.

Given that the length of the cured material is 25 mm (this length is the diameter of the UV light) and the curing time is 1 second, we can substitute these values into the formula to find the speed:

$$v = 25\ \frac{mm}{s}$$

This speed translates to 1.5 m/min.

Therefore, based on the experimental results, the curing process proceeded at a rate of 1.5m/min.

Possible problems:

- The UV curing time is experimented in a static situation and the UV curing process in a pultrusion line is dynamic and probably the times will be different.
- Our light has a circle shape, this shape probably is going to cause problems because the extruded profile has a rectangular shape, and each part will have a different exposure time to UV light.

Possible solutions:

- If the time doesn’t fit and the samples are not curing in a good way, experiment in the pultrusion line, with different speeds.
- Try to use a UV light with a rectangular shape with more than 20 mm width, the length is not important to achieve a better curing degree but the longer the flashlight the higher the speed at which it can be extruded as there is more area of exposure.

6.4. Adaptation to the line.

Once the mold design is finalized, along with the selection of materials and the method for UV light irradiation, including the corresponding time, the last remaining challenge is to adapt the mold to be easily assembled and disassembled on the pultrusion line. Ideally, this versatility will be using universal profiles and fastening elements, allowing for seamless implementation on any pultrusion line. This engineering aspect of mold is crucial to ensure a smooth and efficient transition between different setups, thereby optimizing the flexibility and adaptability of the process.

The initial stage of the solution involves designing and manufacturing the mold.

The mold will comprise six parts, which are 3D printed using PLA.

To assemble the mold, sixteen M6 threaded inserts and a combination of twelve M6 screws measuring 10mm in length and four measuring 35mm in length will be required. Additionally, four screws with a locking device for the rail will be used to lock the mold in the pultrusion line using the metallic brackets.

Assembly plans of the mold are detailed in the Annex II.

After the mold assembling it’s important to assemble it in the real pultrusion line like in the following 3D sketch and the next pictures.

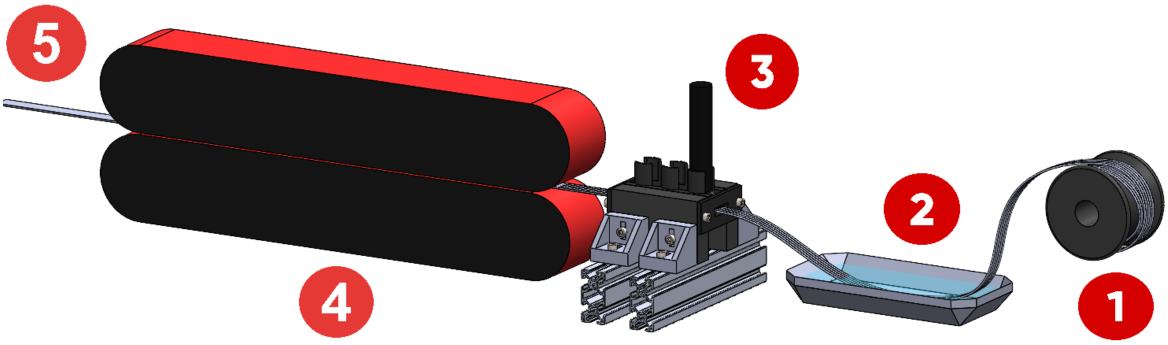


Fig. 6.13 Sketch of UV Pultrusion line assembly.

Source: Own elaboration.

6.5. Experiments using the mold.

The first test on the pultrusion line consisted of a manual haul-off, as the haul-off machine was not used. In this phase, three tests were carried out, each with slightly different results, but all with a common problem: after a short time, usually between 1 and 5 seconds, the composite material would get stuck in the mould causing a clogging.

In all experiments, it's used five roving of 4800 TEX glass fibre, representing approximately 23% of the profile volume. This is lower than the usual proportion used in the pultrusion process.

The steps to carry out this experiment are the following:

- First step is preparing the resin bath and be sure that is completely sealed. In this case the resin bath is so big and we don't have lot of resin so we printed two parts to make the usable part of the resin bath smaller to filled with less resin.

Fig. 6.14 Resin bath.

Source: Own elaboration.

- Next step is assembly the resin bath and the mold into the pultrusion line and put release agent and wait 20 minutes to be completely cured.

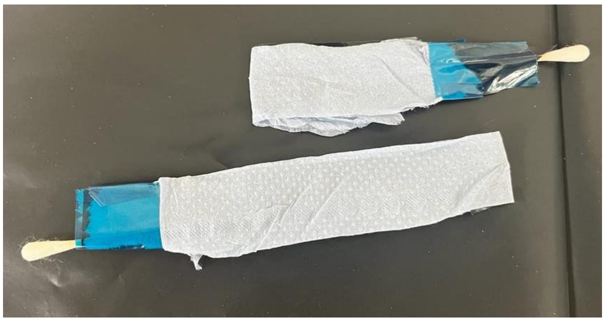


Fig. 6.15 Tool to put release agent.

Source: Own elaboration.

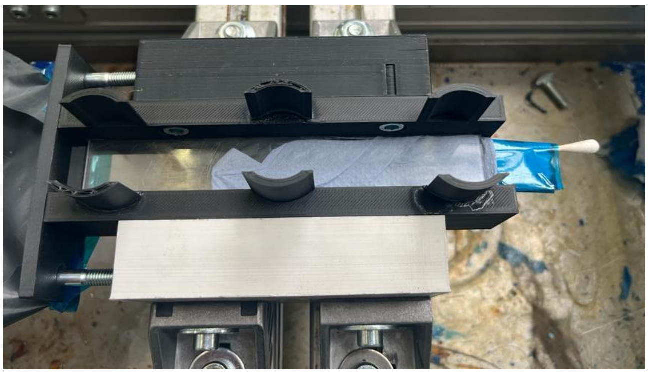


Fig. 6.16 Aplication of release agent inside the mold.

Source: Own elaboration.

The last step is passthrough the glass fibre into the resin bath and the mold, fill the resin bath with resin and start the process.

Fig. 6.17 Pultrusion line assembled.

Source: Own elaboration.

In the first experiment, the results were the least favourable of the three tests. In this case, the composite was exposed to UV-A light for 1 second before getting stuck to the mold. The length of the cured composite exceeded 35 mm, resulting in a pulling speed of 2.3 m/min.

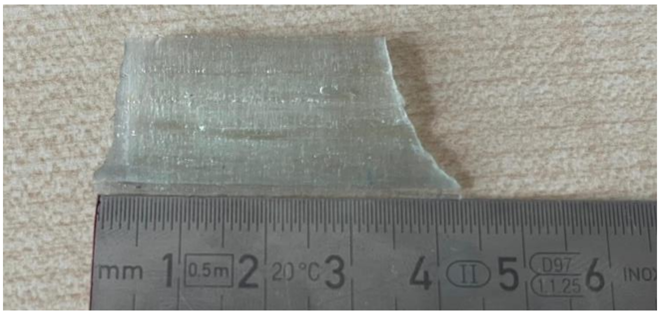


Fig. 6.18 Results the first test.

Source: Own elaboration.

In contrast, the second experiment yielded the most favourable result of the three. In this case, the composite was exposed to UV-A light for 5 seconds before getting stuck to the mold. The cured composite reached a length of more than 160 mm, which required a pulling speed close to 1.9 m/min.

Fig. 6.19 Results the second test.

Source: Own elaboration.

Finally, the results of the last experiment were between the other two tests. In this case, the composite received 3 seconds of exposure to UV-A light before getting stuck to the mold. The length of the cured composite exceeded 115 mm, which justified a pulling speed of around 2.1 m/min.

Fig. 6.20 Results the third test.

Source: Own elaboration.

Several conclusions can be drawn from the results of these experiments, including the following:

- **High Transmission with Quartz Glass Plate:** The first observation is that the transmission of UV-A light through the Quartz Glass plate is exceptionally high. This is indicative of a successful curing process once the UV-A light passes through the plate.
- **Validation of Time Calculation:** The second finding validates the accuracy of our time calculations, which were used to determine pulling speeds. Experiments conducted at speeds close to the calculated values resulted in nearly complete curing of the composite material.
- **Insufficient Fiber Volume:** It is evident that a fibre volume of approximately 23% may not be adequate for the pultrusion process. Future endeavours should consider increasing the fibre volume to optimize the process.
- **Need for Automated Pulling System:** Perhaps the most crucial takeaway is that due to the low curing time, manually pulling the composite is not optimal and possibly is one of the problems because the composite is sticking in to the mold. Maintaining a consistent speed and applying a constant force by hand is challenging. Therefore, the next step should involve implementing a pulling system to assess whether it can yield improved results.

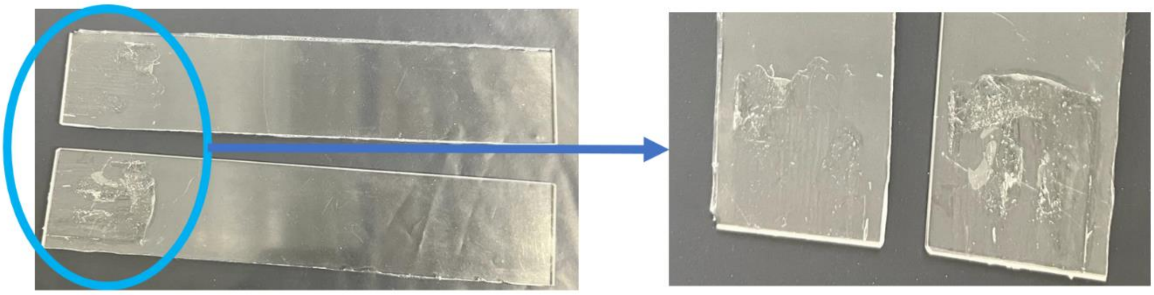


Fig. 6.21 Resin stuck in the plates after opening the experiments.

Source: Own elaboration.

6.6. Experiments using the complete pultrusion line.

This second experiment will be carried out using the pulling system using different constant speeds, the fibre volume of these second experiment is around 41% using 9 roving of 4800 TEX glass fibre.

The preparation of the experiment is basically the same as the previous one, the resin bath and the mold are the same. The difference is the pulling system.

The preparation of the final part involves several sequential steps:

After passing the roving through the mold, they are securely affixed by taping them to a pultruded profile that matches their dimensions. The prepared assembly is then inserted into the pulling system.

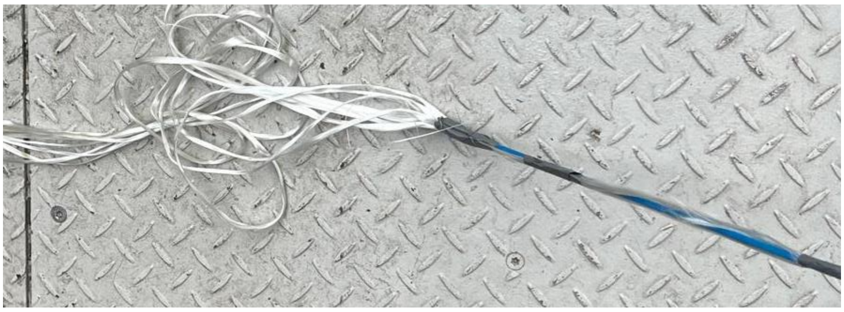


Fig. 6.22 Fibres taped with the pultruded profile.

Source: Own elaboration.

Fig. 6.23 Pulling system with the glass fibre inside.

Source: Own elaboration.

To initiate the process, the pulling system is started at a low speed of 0.3 meters per minute. This initial speed is used just to verify the integrity of the setup.

During this phase, several critical checks are performed:

- The impregnation of the glass fibre is inspected to ensure it meets quality standards.

Fig. 6.24 Glass fibre impregnation in the resin bath.

Source: Own elaboration.

- A thorough examination is conducted to confirm that all the glass fibre roving are being effectively drawn into the system.

Fig. 6.25 Pultrusion line working.

Source: Own elaboration.

Once all the necessary checks have been satisfactorily completed, the process can proceed at the desired speed. For this specific experiment, the following speeds were employed sequentially:

- An initial speed of 1 meter per minute was used.
- Subsequently, a speed of 1.5 meters per minute was adopted.
- Finally, a speed of 0.3 meters per minute was employed.

Fig. 6.27 Commands and screen to set up the pulling speed.

Source: Own elaboration.

The experiment produced a successful result in demonstrating the effectiveness of the UV curing process at various speeds within the pulling system.

The experiments were done at 0.3 m/min, 1 m/min and 1.5 m/min.

Fig. 6.26 Profile using 1 m/min pulling speed.

Source: Own elaboration.

However, there is a main issue to address:

Resin Accumulation in the Mold: The cured resin accumulating inside the mold is obstructing its functionality and making mold disassembly difficult.

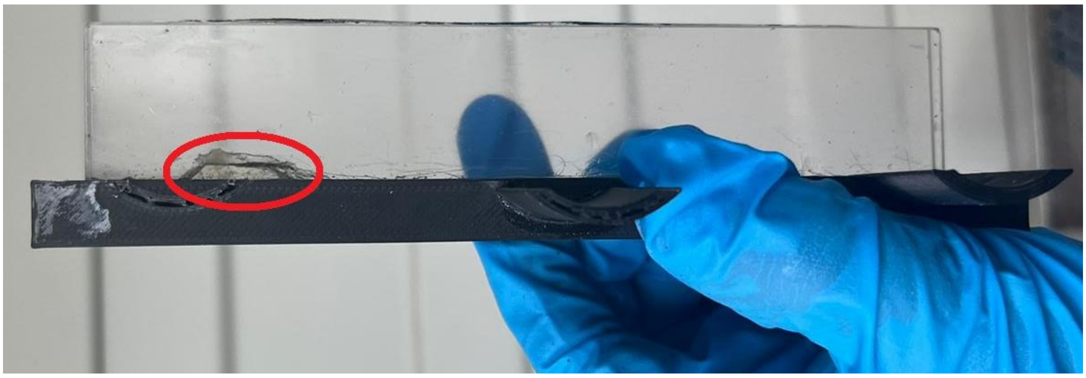


Fig. 6.28 Mold with resin inside after the process.

Source: Own elaboration.

To address these problems, the following steps should be taken:

Redesign the mold: Consider redesigning the mold to incorporate features that prevent excessive resin build-up. Design the mold with disassembly in mind.

6.7. Final mold design.

The second prototype has been successfully completed, incorporating several innovative features. Each UV lamp is securely attached with clamps to ensure they remain in the correct position during the curing process. The base of the mold is designed similarly to the second part of the first prototype, allowing for easy adjustments in the thickness of the composite shape. A significant improvement from the first prototype is the elimination of the common part, simplifying the design and reducing costs. Additionally, this new prototype features UV lights on two sides, ensuring even exposure of the material to the light for better curing results. Overall, these enhancements improve the composite manufacturing process, making it faster, safer, and more effective.

The material for the mold, given the success of the first prototype, the same material will be 3D printed PLA (polylactic acid).

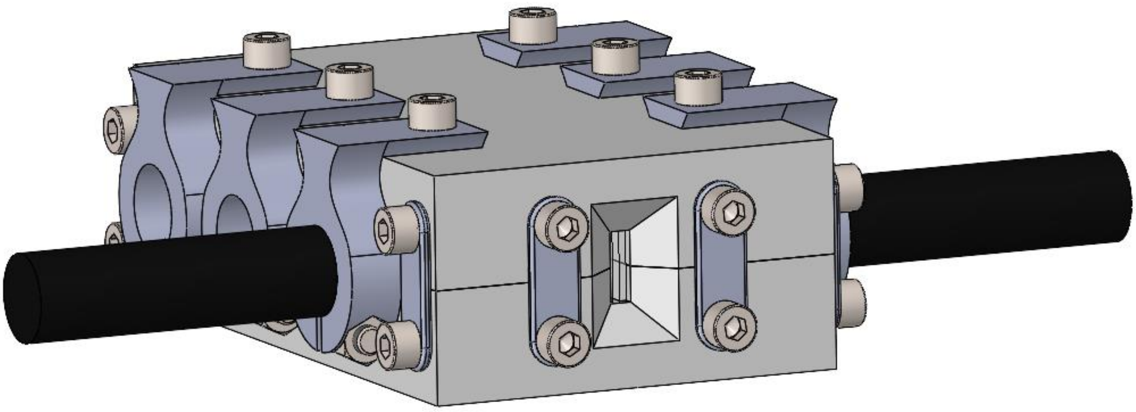


Fig. 6.29 Second prototype for the mold

Source: Own elaboration.

This new mold has been extended from 120 mm in length to 185 mm to accommodate UV lamps on both sides of the mold. The supports for the lamps take up more space than in the previous design. Specifically, this new design will utilize six UV lights, double the amount used in the previous prototype, and, most importantly, it will project light from both sides. This ensures that the material is evenly exposed to UV light, leading to better curing results.

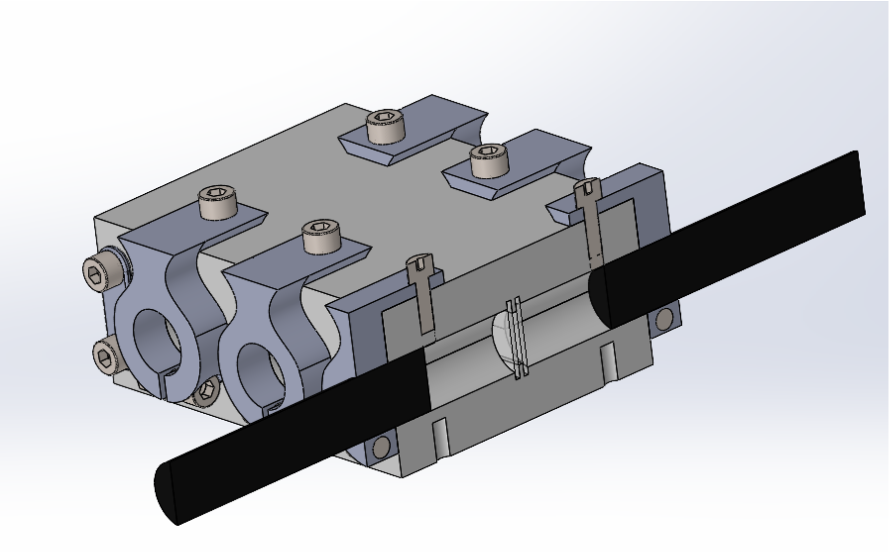


Fig. 6.30 Cut of the second prototype for the mold.

Source: Own elaboration

For the experiments with this new mold, it has been considered interesting to also experiment with UV light at different distances from the composite to be cured. To this end, adjustable supports for the UV lamps have been designed, which can be secured with screws to hold them at the desired height. This adjustability will allow us to study how the distance of the UV light affects the curing time and quality of the composite, providing valuable data to optimize the curing process and ensure maximum efficiency and effectiveness.

To determine the optimal height for positioning the lamps in the initial experiments, a 3D-printed mold has been designed. This mold features grooves at different heights where the quartz glass is inserted. The design is divided into two parts, which will also be included in the document annex with detailed plans. This innovative approach will help fine-tune the placement of the UV lamps, ensuring the best curing results.

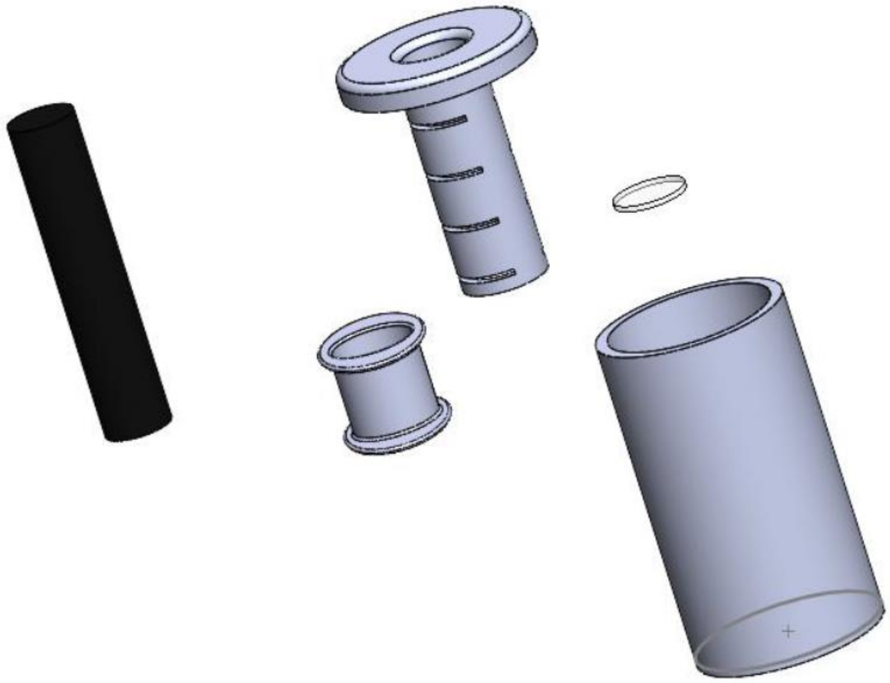


Fig. 6.31 Curing tester mold.

Source: Own Source.

With these static experiments using the mold, the aim is to compare whether the distance at which the UV light acts is also important. If the results indicate that the distance has a significant impact on the curing process, experiments will then be conducted at various distances in the pultrusion line using the new mold. This experimental phase is crucial for optimizing the process and ensuring that the composite materials cure uniformly and efficiently.

The Blueprints of this Curing Tester and the Blueprints of the Second mold are available in the Blueprints document.

7. Viability

7.1. Technical Viability.

Currently, there are studies supporting the feasibility of curing composite materials using ultraviolet (UV) light. As previously mentioned, two doctoral theses have explored pultrusion with UV curing outside the mold. [4] The primary challenge of this project lies in developing a specific method for curing inside the mold.

To address this challenge, the use of quartz glass is proposed to take advantage of its high transmittance at the wavelength of ultraviolet type A (UV-A) light. This approach ensures that UV-A light is effective in the composite material during the curing process, thereby enhancing its quality and efficiency. This step is crucial for optimizing UV curing in pultrusion technology, allowing for its effective and controlled application within the mold.

This material is essential to carry out the project as it is one of the few existing transparent materials that allow UV-A light to pass through without disturbing the wavelength and offers a high transmittance at the wavelength of our light source (365nm).

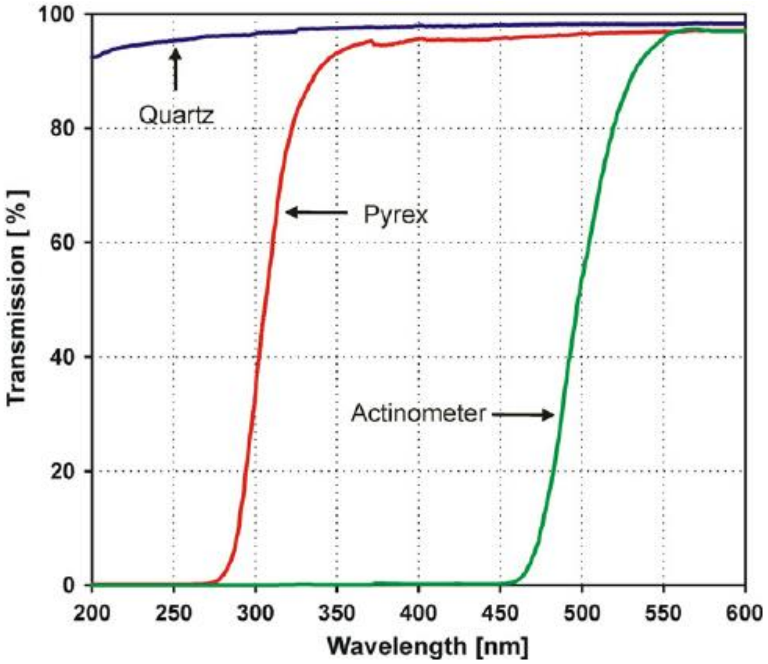


Fig. 7.1 Chart about Transmission (%) – Wavelength (nm)

Source: [14]

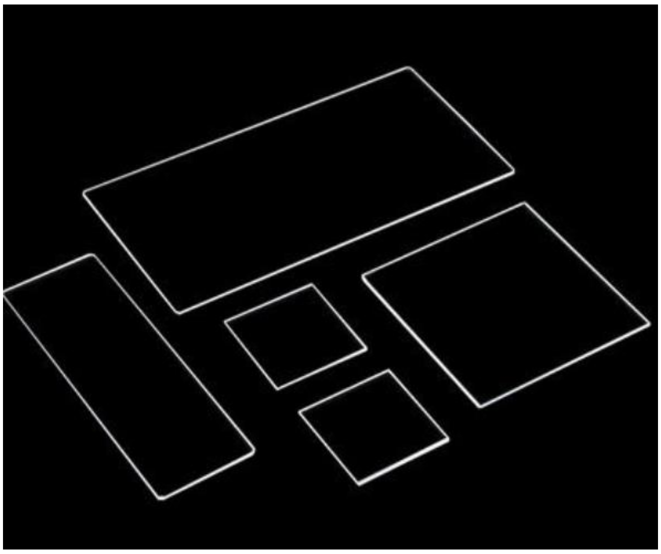


Fig. 7.2 Quartz Glass Plates.

Source: [15]

Quartz Glass sheet:

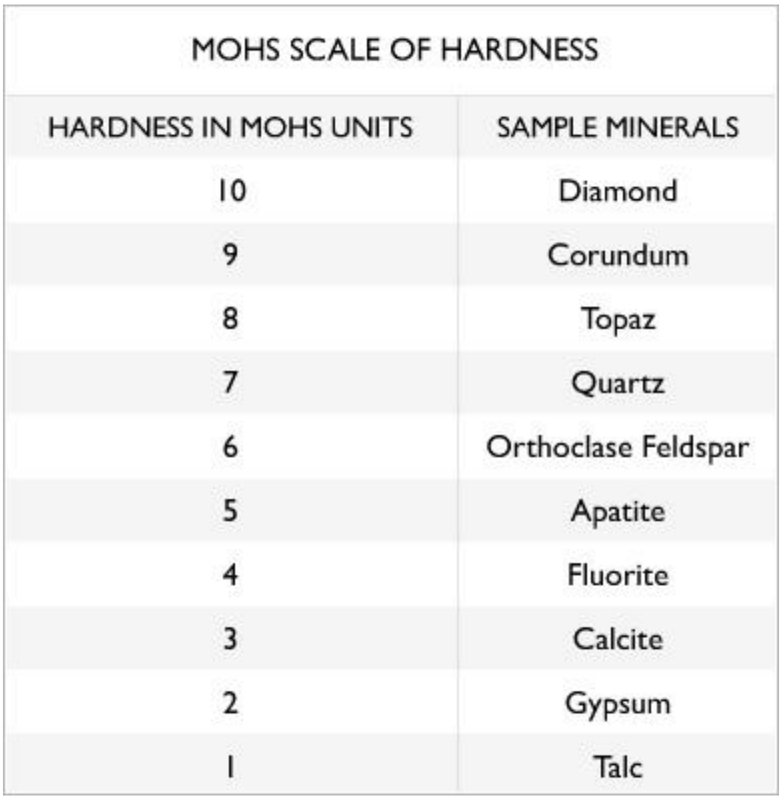
The measures of the Quartz Glass plates are 100 mm x 30 mm x 2 mm.

Properties about the Quartz Glass using a UV light with a wavelength of 360nm:

- Refractive index = 1.47529
- T (%) ≈ 93%

Source: Quartz Glass Datasheet.

Quartz glass has a hardness of 7 on the Mohs scale, where 10 is the highest value, represented by diamond. Its thermal properties are ideal for this application due to its low thermal expansion coefficient of 5.5 × 10^-7 cm/cm°C, which provides exceptional thermal stability. Additionally, the chemical properties of quartz glass are highly advantageous, as it is inert to the majority of chemical components, making it a durable and reliable choice for molds in UV curing processes.



MOHS SCALE OF HARDNESS

HARDNESS IN MOHS UNITS	SAMPLE MINERALS
10	Diamond
9	Corundum
8	Topaz
7	Quartz
6	Orthoclase Feldspar
5	Apatite
4	Fluorite
3	Calcite
2	Gypsum
1	Talc

Table 7.1 Mohs Scale.

Source: [16]

About composite:

The vast majority of pultrusion profiles use a ratio of 60% fibers by volume and 40% resin by volume, so it is necessary to know how much fiber is required for the particular profile to be extruded.

In the case the area of the pultruded profile is 40 mm² so the area which must be filled with glass fiber is 24 mm².

For the pultrusion process spools of glass fibers are used, these spools are measured in TEX and the most common used in process are the 2400 TEX and the 4800 TEX. These fiber spools are standardized by means of a patent that standardizes the number of wires and the diameter of the wires for each of the nomenclatures.

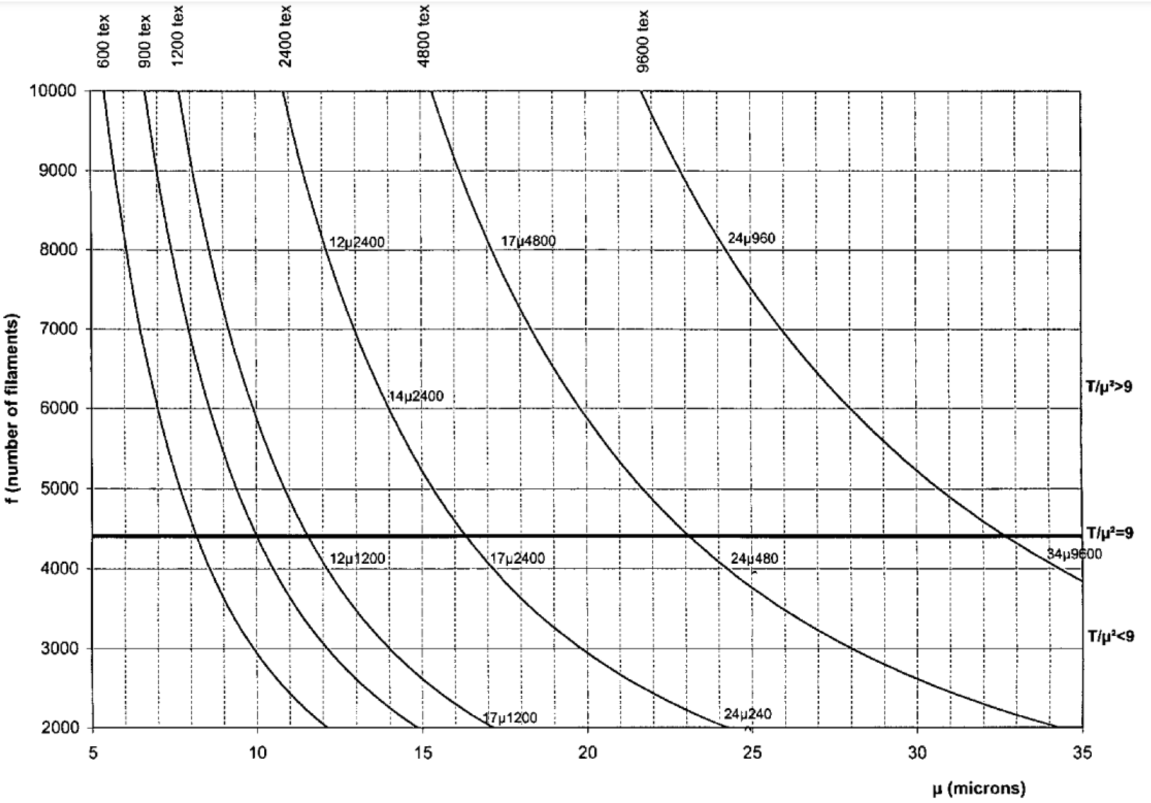


Fig. 7.3 *Chart of: f (number of filaments) – Diameter of filament (μm)*

Source: [17]

Calculations to find the nº of glass fiber spools need:

$$A_f = \pi \cdot r^2 \qquad (eq. 7.1)$$

$$A_t = A_f \cdot f \qquad (eq. 7.2)$$

$$n = \frac{A}{A_f} \qquad (eq. 7.3)$$

Nomenclature	ø (µm)	$A_{60\%}$ (mm^2)	A_f (mm^2)	A_t (mm^2)	f (nº filaments)	n (nº spools)
2400 TEX	17	24	0,00022698	0,907920088	4000	26,43404449
4800 TEX	17	24	0,00022698	1,815840176	8000	13,21702225
4800 TEX	24	24	0,000452389	1,809556992	4000	13,26291468

Table 7.2 Results of nº spool need.

Source: Own Elaboration.

After careful evaluation, it has been determined that the utilization of the 4800 TEX is the optimal solution. This choice is primarily driven by the constrained capacity of the spool warehouse within our pultrusion line, which consists of only 16 slots. The usage of the 2400 TEX it's possible but it would be a challenge, as it needs the utilization of multiple spools within certain slots.

If in the experiment is used 13 spools of 4800 TEX with filaments of Ø17 (µm) or Ø24 (µm), the proportions will be 59% glass fibre and 41% resin.

If in the experiment is used 14 spools of 4800 TEX with filaments of Ø17 (µm) or Ø24 (µm), the proportions will be 63.55% glass fibre and 36.45% resin.

About curing time (Mathematic Model).

This mathematic model is based on the Beer-Lambert Law, is an optic model which is based on the absorption of the composite over time. The absorption of the composite is based on the Intensity before the composite and after that.

Nomenclature:

- Io λ = incident intensity at a specific wavelength (W/m²).
- IT λ = transmitted intensity at a specific wavelength (W/m²).
- A λ = absorbance at a wavelength specific concentration of photoinitiator system.

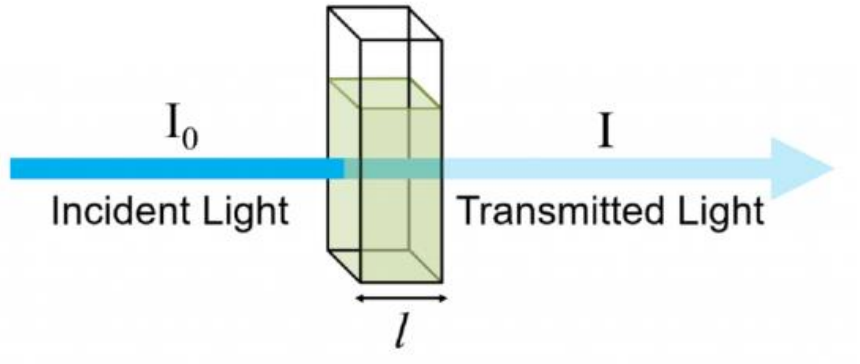


Fig. 7.4 Transmission of light through a sample solution in a cuvette.

Source: [18]

$$I_\mathrm{T} = \int I_{\mathrm{T}_\lambda} \cdot \mathrm{d}\lambda \qquad A_\lambda = \log\left(\frac{I_{0_\lambda}}{I_{\mathrm{T}_\lambda}}\right) \qquad I_{\mathrm{T}_\lambda} = 10^{(\log I_{0_\lambda} - A_\lambda)}$$

In order to apply this mathematic model, an experiment must be carried out to collect the necessary data.

This experiment is interesting as it is not complex to perform and is used to find out how long it takes to polymerise a composite of a specific thickness, using a specific UV light source that has a specific wavelength and output intensity.

The process is based on taking data on the light intensity before and after passing through the composite several times until the composite is cured. This is done because at the beginning the absorbance is very high as the photoinitiators have not initially decomposed into free radicals, the purpose is to find at what point they start to decompose and at what point the composite is fully cured, the latter is found when the absorbance and the transmitted intensity tend to be on a horizontal asymptote.

Material needed for the experiment:

- Resin and glass fibre.
- UV light source.
- Quartz glass cuvette for the resin with specific thickness.
- Lux meter or Radio meter UVA.

The lux meter measures light intensity in units of LUX, which can be converted to W/m2 using the conversion factor 1 LUX = 0.0079 W/m2. That factor is used for the solar light.

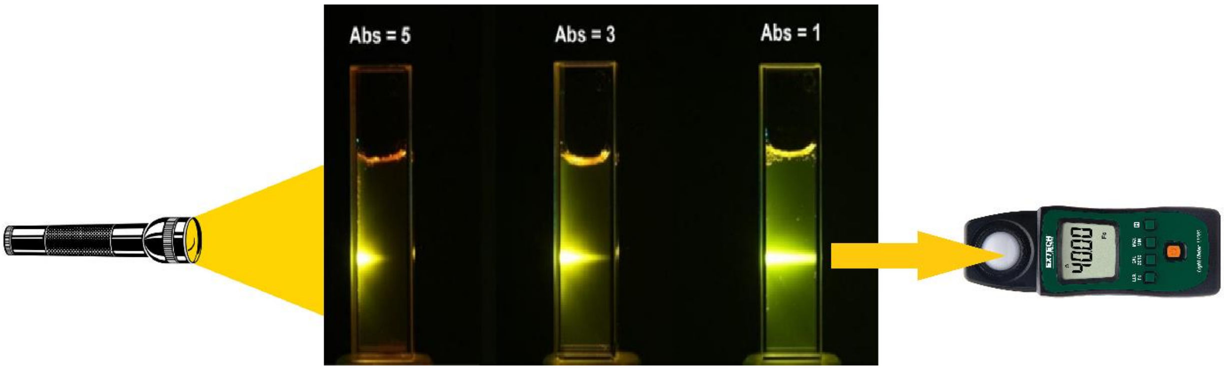


Fig. 7.5 Sketch for the experiment.

Source: Own Elaboration.

The aim is to carry out experiments by altering one variable at a time, such as changing the level of resin, modifying the thickness or adjusting the intensity of the light by altering the distance of the UV flashlight or possibly utilizing multiple flashlights in order to increase the intensity.

What is a Release Agent and How Does it Work?

A release agent is a chemical substance that forms a thin, uniform film on the surface of the mold. This film acts as a barrier between the mold and the composite material, facilitating the separation of the cured product from the mold without damaging the surface of either.

The proper use of release agents is essential in the pultrusion process with UV curing for the following reasons:

Prevention of Adhesion: During curing, if the composite material sticks to the mold, it can result in a defective final product. This not only affects the precise shape and dimensions of the composite but can also damage the mold, increasing maintenance and repair costs.

Ease of Extraction: Release agents allow for the smooth extraction of the cured product from the mold, which is crucial for maintaining the structural integrity and surface quality of the composite.

Increased Process Efficiency: By reducing the time and effort required to extract the cured composite from the mold, release agents improve the efficiency of the production process, allowing for faster manufacturing cycles and less downtime.

Mold Protection: Release agents protect the mold surface from damage and premature wear, extending the mold's lifespan and reducing long-term operational costs.

7.2. Ambiental Viability.

- **Positive environmental aspects:**

Reduced energy consumption: A significant reduction in energy consumption is one of the most favourable aspects from an environmental point of view. This could contribute to the reduction of greenhouse gas emissions and the carbon footprint associated with pultrusion production.

Resin reuse: The ability to reuse resin can reduce the amount of waste and minimise reliance on new raw materials. This would contribute to sustainable resource management and decrease the environmental impact associated with resin waste production and disposal.

Reduced waste generation: Process optimisation, together with the reuse of materials, can reduce the amount of waste generated during production. This could have significant environmental benefits by reducing the amount of waste going to landfill.

Potential improvement in end-product durability: If UV-curable pultrusion results in end products with superior properties, such as increased durability and strength, it could lead to longer product lifetimes and thus a reduction in the need for frequent replacements.

- **Considerations and potential challenges:**

Impact of UV curing technology: the implementation of UV curing technology may have its own environmental impacts, such as the generation of waste related to UV lamps or the need for specific curing chemicals (photoiniciators). It is important to assess these aspects.

Life cycle analysis: A full life cycle analysis of the product should be carried out, from the extraction of raw materials to the final disposal of the product. This will help to identify critical areas and opportunities to improve sustainability throughout the entire process.

Potential social impacts: In addition to environmental aspects, it is also important to consider the social impacts of the change, such as training of employees for the new technology and possible changes in the supply chain.

7.2.1. Energy consumption.

To compare the consumption of a conventional pultrusion line with that cured using UV light, a study carried out in 2022 has been chosen that tries to optimize energy consumption in a conventional pultrusion line. The study was carried out with the objective of improving productivity, effectiveness, and energy consumption in conventional pultrusion, starting from an initial consumption of 24.8 W/m. Optimizing processes in the pultrusion line is crucial to reduce operating costs and environmental impact, as well as increase production efficiency. Through a series of experiments and adjustments to the line configuration, power consumption was reduced to 14.2 W/m. [19]

Comparing these results with the experiments carried out on the UV curing pultrusion line, it is observed that the latter uses a 1.1 W light source and is capable of extruding at a speed between 1 m/min and 1.5 m/min, resulting in significantly lower power consumption of approximately 1.1 W/m and 0.73W/m.

Conventional Pultrusion Line:

- Power consumption: 14.2 W/m.

UV Curing Pultrusion Line:

- Light source: 1.1 W.
- Extrusion speed: 1.5 m/min.
- Power consumption: 1.1 W / 1.5 m = 0.73 W/m.

Advantages in Energy Consumption

The UV curing pultrusion line presents a significant advantage in terms of energy consumption, with a consumption of approximately 0.73 W/m, compared to 14.2 W/m for the conventional line. This represents a reduction in energy consumption of more than 90%.

7.2.2. Impact of photoiniciators.

Photoinitiators can affect the environment in various ways, mainly through their persistence and toxicity in aquatic and terrestrial ecosystems. Photoinitiators are chemical compounds that, when exposed to ultraviolet (UV) light, initiate the polymerization of resins and other materials. However, some of these compounds can be harmful to the environment and carry the following label GHS09 so that the consumer tries to use them correctly:

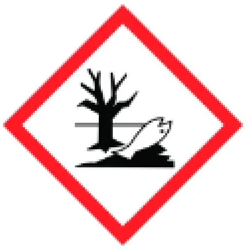


Fig. 7.6 Label GHS09 (substances harmful to the aquatic environment.)

Source: [20]

Aquatic Toxicity: Some photoinitiators are toxic to aquatic organisms. They can cause adverse effects on the growth and reproduction of algae, daphnia and fish, thus affecting the health of aquatic ecosystems.

Persistence in the Environment: Many photoinitiators do not break down easily and can accumulate in ecosystems. This persistence can lead to bioaccumulation in aquatic organisms, affecting the food chain and biodiversity.

Soil and Water Pollution: The release of photoinitiators during the production, use and disposal of cured materials can contaminate soil and groundwater. This shows that these compounds can escape conventional water treatment systems.

To minimize the environmental impact of photoinitiators, less toxic compounds must be developed, waste properly managed, and strict monitoring programs and regulations established.

In summary, the transformation project seems to have several positive aspects from an environmental point of view, especially in terms of reduced energy consumption and reuse of materials. However, a more detailed and specific analysis is recommended to fully assess the environmental impact of the project and address possible challenges.

In the environmental report annex, detailed tables can be found outlining the points where the project may have an impact, along with a brief conclusion on the effects.

7.3. Economic Viability.

The economic viability of the project is based on the potential and growing global market demand for pultrusion which has applications in various sectors such as industrial, housing, civil engineering, and aeronautics. Pultrusion, as a continuous and automated system to produce polyester profiles reinforced with glass fibre and other reinforcements, has proven to be crucial in the manufacture of durable and lightweight components.

According to available data, the market volume of pultrusion reached USD 2.90 billion, with an annual growth rate of close to 5% until 2029. This indicator suggests a positive trend in demand for pultruded products, which could translate into growth opportunities for an adapted pultrusion line with UV curing technology.

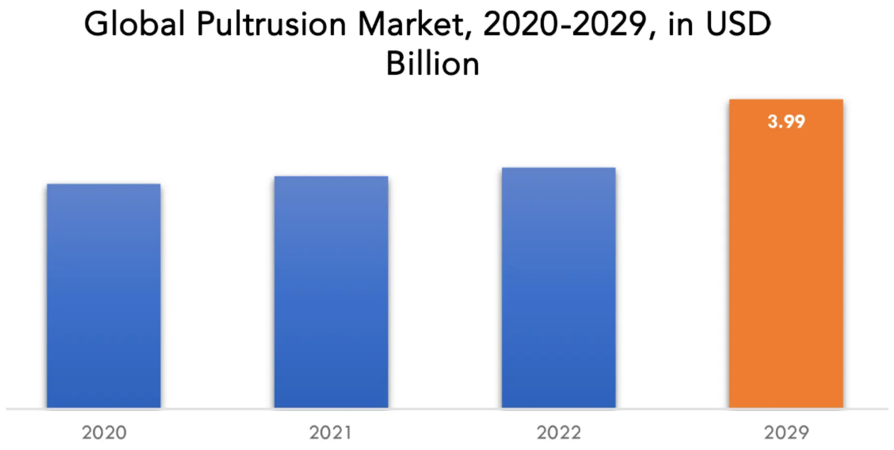


Fig. 7.7 Global Pultrusion Market in USD.

Source: [21]

The initial budget for this project is 43,837 euros, which is not very significant considering the potential impact on the pultrusion industry. The successful implementation of UV curing technologies could improve the efficiency of the pultrusion process, increase the quality of the final products and ultimately boost competitiveness in the market.

Importantly, this modification to the pultrusion process using UV light curing will reduce energy consumption and waste generated when compared to the conventional curing process.

7.3.1. BUDGET

Total Chapter I	33.250,00 €
Total Chapter II	304,23 €
Total Chapter III	2674,74 €
TOTAL	36.228,97 €
IVA 21 %	7.608,08 €
TOTAL BUDGET	**€43.837,05**

This budget is detailed in the Chapter 9 of this document and in the Economic study.

8. Planification.

In the field of engineering, detailed project planning plays an essential role in achieving objectives efficiently and effectively. This document presents the comprehensive planning of the project, in which all tasks will be executed by Roger Juiz, a mechanical engineer student.

Regarding the time distribution of the project, it is divided into two strategic phases:

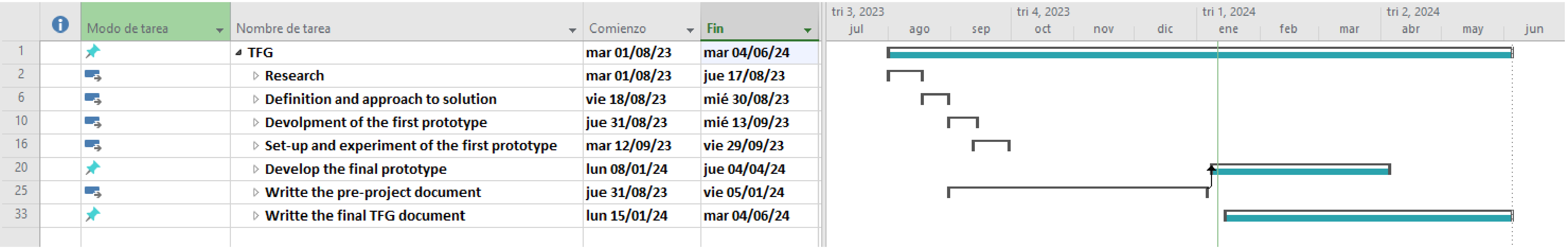
Initial Phase (August and September 2023):

During this intensive phase, with a dedication of 40 hours per week over 9 weeks, 360 hours will be invested in the in-depth understanding and application of the complexities linked to pultrusion using UV light technology. In addition, the design and manufacture of the first prototype will be carried out in this initial phase.

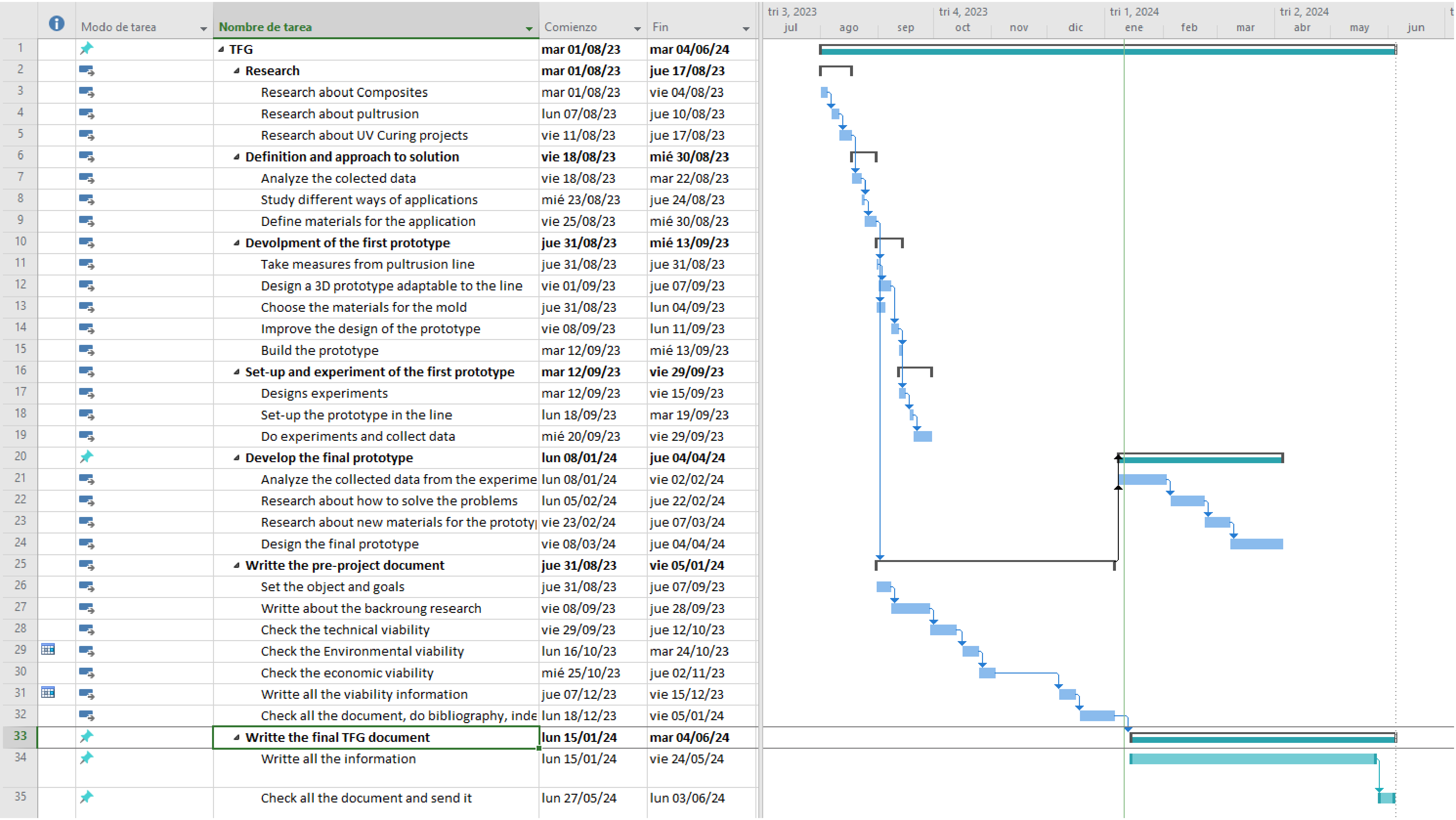
Second Phase (October 2023 - 3 June 2024):

From October 2023, the workload will be reduced to 10 hours per week. This decision is based on the need to reconcile academic and extracurricular responsibilities. During this transition phase, 350 hours will be allocated to thoroughly document the entire project, as well as to study and design a final improved mold prototype.

Below is a Gantt chart detailing all the activities to be carried out in the project with their respective start and end dates.



	ℹ	Modo de tarea	Nombre de tarea	Comienzo	Fin
1		📌	◢ TFG	mar 01/08/23	mar 04/06/24
2		➡	▷ Research	mar 01/08/23	jue 17/08/23
6		➡	▷ Definition and approach to solution	vie 18/08/23	mié 30/08/23
10		➡	▷ Devolpment of the first prototype	jue 31/08/23	mié 13/09/23
16		➡	▷ Set-up and experiment of the first prototype	mar 12/09/23	vie 29/09/23
20		📌	▷ Develop the final prototype	lun 08/01/24	jue 04/04/24
25		➡	▷ Writte the pre-project document	jue 31/08/23	vie 05/01/24
33		📌	▷ Writte the final TFG document	lun 15/01/24	mar 04/06/24



	Nombre de tarea	Comienzo	Fin
1	**TFG**	**mar 01/08/23**	**mar 04/06/24**
2	**Research**	**mar 01/08/23**	**jue 17/08/23**
3	Research about Composites	mar 01/08/23	vie 04/08/23
4	Research about pultrusion	lun 07/08/23	jue 10/08/23
5	Research about UV Curing projects	vie 11/08/23	jue 17/08/23
6	**Definition and approach to solution**	**vie 18/08/23**	**mié 30/08/23**
7	Analyze the colected data	vie 18/08/23	mar 22/08/23
8	Study different ways of applications	mié 23/08/23	jue 24/08/23
9	Define materials for the application	vie 25/08/23	mié 30/08/23
10	**Devolpment of the first prototype**	**jue 31/08/23**	**mié 13/09/23**
11	Take measures from pultrusion line	jue 31/08/23	jue 31/08/23
12	Design a 3D prototype adaptable to the line	vie 01/09/23	jue 07/09/23
13	Choose the materials for the mold	jue 31/08/23	lun 04/09/23
14	Improve the design of the prototype	vie 08/09/23	lun 11/09/23
15	Build the prototype	mar 12/09/23	mié 13/09/23
16	**Set-up and experiment of the first prototype**	**mar 12/09/23**	**vie 29/09/23**
17	Designs experiments	mar 12/09/23	vie 15/09/23
18	Set-up the prototype in the line	lun 18/09/23	mar 19/09/23
19	Do experiments and collect data	mié 20/09/23	vie 29/09/23
20	**Develop the final prototype**	**lun 08/01/24**	**jue 04/04/24**
21	Analyze the collected data from the experime	lun 08/01/24	vie 02/02/24
22	Research about how to solve the problems	lun 05/02/24	jue 22/02/24
23	Research about new materials for the prototy	vie 23/02/24	jue 07/03/24
24	Design the final prototype	vie 08/03/24	jue 04/04/24
25	**Writte the pre-project document**	**jue 31/08/23**	**vie 05/01/24**
26	Set the object and goals	jue 31/08/23	jue 07/09/23
27	Writte about the backroung research	vie 08/09/23	jue 28/09/23
28	Check the technical viability	vie 29/09/23	jue 12/10/23
29	Check the Environmental viability	lun 16/10/23	mar 24/10/23
30	Check the economic viability	mié 25/10/23	jue 02/11/23
31	Writte all the viability information	jue 07/12/23	vie 15/12/23
32	Check all the document, do bibliography, inde	lun 18/12/23	vie 05/01/24
33	**Writte the final TFG document**	**lun 15/01/24**	**mar 04/06/24**
34	Writte all the information	lun 15/01/24	vie 24/05/24
35	Check all the document and send it	lun 27/05/24	lun 03/06/24

9. Budget

9.1. Measurements

This chapter includes the measurements corresponding to the engineering (design and development of the solution) and the materials used in the realization of the prototype.

Chapter I: Elaboration of the project		
Code	**Description**	**Equal parts**
1.1	Hours spent on research background and information needs.	110
1.2	Hours dedicated to the definition and approach of the solution.	50
1.3	Hours spent on the development and design of the first solution	90
1.4	Hours of designer destined to the realization and commissioning of the first prototype.	110
1.5	Hours of design and improvement of the first prototype.	130
1.6	Hours devoted to research and written preparation to prepare the documents of the preliminary project.	100
1.7	Hours allocated to research and written elaboration to carry out the project documents.	170

Chapter II: Material		
Code	**Description**	**Equal parts**
2.1	PLA 1.75mm 1Kg. [22]	1
2.2	Quartz Glass 2mm thick.	2
2.3	4800 TEX Glass fiber. [23]	10
2.4	UV – Resin.	1
2.4	UV Convoy FlashLight.	1

9.2. Price chart.

Chapter I: Elaboration of the project		
Code	**Units (Hours)**	**Unit price (€)**
1.1	110	35
1.2	50	35
1.3	90	35
1.4	110	35
1.5	130	35
1.6	100	35
1.7	170	35

Chapter II: Material		
Code	**Units**	**Unit price (€)**
2.1	1	18,99
2.2	2	80,00
2.3	10	6,00
2.4	1	0,00

9.3. Partial budget.

Chapter I: Elaboration of the project				
ENGINEERING COST[1]				
Code	**Description**	**Total units**	**Unit price (€)**	**Import (€)**
1.1	Hours spent on research background and information needs.	110	35	3.850
1.2	Hours dedicated to the definition and approach of the solution.	50	35	1.750
1.3	Hours spent on the development and design of the first solution	90	35	3.150
1.4	Hours of designer destined to the realization and commissioning of the first prototype.	110	35	3.850
1.5	Hours of design and improvement of the first prototype.	130	35	4.550
1.6	Hours devoted to research and written preparation to prepare the documents of the preliminary project.	100	35	3.500
1.7	Hours allocated to research and written elaboration to carry out the project documents.	170	35	5.950
INDIRECT COSTS				
1.8	Indirect labour costs			6.650

TOTAL CHAPTER I (25% margin) **33.250,00 €**

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[1] Results of planning and resource allocation

Chapter II: Material				
PROTOTYPE MATERIAL COSTS				
Code	**Description**	**Total units**	**Unit price (€)**	**Import (€)**
2.1	PLA 1.75mm 1Kg	1	18,99	18,99
2.2	Quartz Glass 2mm thick	2	80,00	160,00
2.3	4800 TEX Glass fiber.	10	6,00	60,00
2.4	UV - Resin[2]	1	0,00	0,00
2.5	UV Convoy FlashLight	1	25,56	25,56
INDIRECT COSTS				
2.42	Indirect material costs			39,68

TOTAL CHAPTER II (15% of unforeseen events): **€304,23**

Chapter III: Amortizations[3]				
COMPUTER EQUIPMENT AND SOFTWARE				
Code	**Description**	**Cos Inv.**	**N (years)**	**€/year**
3.1	Laptop MSI GF63 Thin 12VE-026ES [24]	899	3	299,99
3.2	Software SolidWorks Student	0	3	0
3.3	Software Microsoft Office	0	3	0
LABORATORY EQUIPMENT				
3.6	Pultrusion line. [25]	20.000	10	2.000,00
3.7	3D printer [26]	1.499	4	374,75

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[2] The UV-Resin used is not inherently free, it was provided by Allnex to ILK for experimental purposes

[3] Amortizations are calculated in the case of carrying out 1 project per year

TOTAL CHAPTER III	**2.674,74 €**

9.4. Final budget.

Total Chapter I	33.250,00 €
Total Chapter II	304,23 €
Total Chapter III	2674,74 €
TOTAL	36.228,97 €
IVA 21 %	7.608,08 €
TOTAL BUDGET	**€43.837,05**

The preparation of this project generates the indicated expenses.

10. Conclusions

The integration of a UV source for light-based curing of continuous fibre composites into the pultrusion process has proved to be a successful venture. This project started with a thorough investigation of the curing process and reviewed several existing projects on UV curing in pultrusion. However, the novel approach of curing within the mould had not previously been explored and this provided a big objective for our research.

Through careful design, manufacture and experimentation with our first prototype mould, we demonstrated the feasibility of this innovative process. The results were promising and confirmed that UV curing in the mould was indeed possible and effective. While this success was significant, it was accompanied by the typical challenges associated with research projects. Certain aspects required refinement, which led us to design a second prototype mould.

The new mold design focused on simplification, reducing the number of components, and incorporating UV light sources on both sides to further improve the curing process further. This redesign aims to address the imperfections observed in the first prototype and improve the overall efficiency and effectiveness of the curing process.

The project also demonstrated the economic, environmental and technical viability of this novel pultrusion process. In comparison, our UV curing process demonstrated significant improvements over conventional pultrusion techniques, with energy savings of up to 90% and significantly faster curing times. While conventional pultrusion processes operate at an extrusion speed of 1 to 1.5 metres per minute, our initial trials of the new UV curing process have achieved the same speed. This speed parity, combined with other benefits, underlines the promising future of this technology.

10.1. Future directions of the project.

It is important to emphasise that this project marks the beginning of the development of the UV in-mold pultrusion process, which suggests that further experimentation with this method could be very interesting and beneficial. One of the future steps of this project would be to compare the curing degree of the composite obtained with that of a composite produced by the conventional method. Continued experimentation until the same level of cure is achieved will allow us to determine whether this technology represents the future of pultrusion.

Successful integration of this process has the potential to revolutionise the industry by offering a more efficient, cost effective and environmentally friendly alternative to traditional methods.

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