POLITECNICO DI TORINO

Collegio di Ingegneria Chimica e dei Materiali

Master of Science Course
in Materials Engineering for Industry 4.0

Master of Science Thesis

Development of High-Temperature-Resistant DLP 3D Printed Molds for Carbon Fiber Lamination in Autoclave Processes: Applications in Customized and Structural Components

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October 2025

To Francesca, who has always been there for me.

Acknowledgement

First and foremost, I am deeply grateful to my family for their unwavering support throughout this journey. Their constant presence has shown me that any challenge can be faced when surrounded by those we love.

A heartfelt thank you goes to Cris- considered part of the family- for his steady support and presence at every stage of this experience.

To my friends in Turin- especially Sofia, Luca, Thomas, Giacomo, and Gabri- sharing this time with you has made the path lighter, more enjoyable, and filled with unforgettable moments. A special mention goes to Giacomo, whose help during the realization of this project has been invaluable.

Muchas gracias to Peppe, for teaching me to take life a little less seriously and to enjoy the ride.

To Antonia, my sister and true friend- thank you for always being by my side.

I would also like to express my sincere thanks to Professors Adrian and Jumna for their guidance and support. They gave me the opportunity to turn theoretical knowledge into practical experience, and to approach research with curiosity and confidence.

Grateful to share this achievement with all of you, I extend my thanks to everyone who has accompanied me over these past two years. Your presence has truly made a difference.

Abstract

This work investigates the potential of additive manufacturing (AM) as a cost- and time-effective alternative for producing molds suitable for autoclave curing of carbon fiber prepregs laid up manually. The study focuses on two application domains: biomedical devices and structural components. The methodology combines CAD-based mold design, digital light processing (DLP- LCD) 3D printing, manual lamination of prepregs, autoclave curing, and final evaluation of the mold's performance.

The results highlight the viability of AM for low-volume, customized production- especially in biomedical applications, where geometrical complexity and personalization are key. In this context, the printed molds demonstrated excellent thermal resistance and dimensional accuracy, proving fully compatible with the curing process.

However, for structural components requiring higher dimensional stability and repeatability across multiple curing cycles, limitations emerged. In particular, when the mold could not be printed as a single monolithic part due to size constraints, deformation occurred at the joint interfaces. This was caused by the non-uniform release of residual stresses during the autoclave cycle, which compromised the alignment and reusability of the mold. These issues were further exacerbated by the larger dimensions and structural function of the part, highlighting the need for improved joint design and stress management in modular molds.

From a scientific and industrial perspective, this approach shows strong promise as a prototyping tool, offering fast iteration and design validation. Future research should address mold modularity, stress-relief strategies, and the long-term reliability of printed molds under repeated thermal cycles to enable broader adoption in high-performance composite manufacturing.

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1. Introduction, Objective and Motivation

This chapter introduces composite materials, emphasizing their relevance in material science, engineering design, and modern industry. It will also outline the experimental context and the motivations behind the choice of the topic for this thesis.

1.1. The Importance of Composite Materials

A composite material, in its broadest definition, is an engineered system consisting of a combination of two or more macroscopically distinguishable components: a continuous phase, called the *matrix*, and a dispersed phase, the *reinforcement*. These two phases are designed to work in synergy to achieve superior physical and mechanical properties compared to each component taken individually [1][2].

Unlike other multiphase materials, such as metal alloys, copolymers, or cementitious conglomerates, composites have an intentionally designed microstructure to meet specific functional objectives, optimizing parameters such as orientation, volume fraction, reinforcement geometry, and interface quality between the phases [2].

Although the use of composite materials has ancient origins- for example, the combination of mud and straw in bricks used by the Egyptians- it was from the 1950s onward, with the development of high-performance synthetic fibers (glass, aramid, and carbon), that they began to be systematically employed in modern structural engineering [3]. Since then, composites have become an extremely versatile material capable of effectively meeting advanced design requirements.

Their characteristics, such as high strength-to-weight ratio, lightweight, corrosion resistance, and the ability to create complex shapes at relatively low costs, make them ideal for a wide range of applications (paragraph 1.2). Additionally, they offer exceptional fatigue resistance, impact and vibration tolerance, high fire response, and remarkable durability in chemically aggressive environments. Composite materials also provide additional benefits, including electrical insulation, dimensional stability (due to low thermal conductivity and reduced expansion), functional integration potential, and a high-quality aesthetic finish [3].

1.2. Applications in Leading Industrial Sectors

The perfect balance between innovation and functionality translates into flexible solutions across various industrial sectors.

In the aerospace sector, composite materials are widely used due to their high specific strength and ability to reduce the overall weight of structures. Currently, about 50% of a modern aircraft's structure is made of composites. These materials are employed in critical components such as rudders, spoilers, aerodynamic brakes, elevators, engine nacelles, wing spars, and turbine blades, also facilitating the assembly process.

In the automotive sector, the need to decrease vehicle weight and improve fuel efficiency has driven the widespread adoption of composites, particularly those reinforced with glass or carbon fibers and epoxy matrices. Their applications range from steering wheels and dashboards to roofs, tailgates, seats, wheels, interior and exterior panels, and engine covers.

In the biomedical field, composites are used in various non-vital devices designed for interaction with the human body. Advances in synthetic materials and sterilization technologies allow their use in sutures, bone and joint prostheses, heart valves, intraocular lenses, pacemakers, biosensors, significantly enhancing patients' quality of life.

In the electronics sector, composites are designed to offer specific properties such as high thermal conductivity, low thermal expansion coefficient, and customized dielectric constants. They are utilized in applications such as electrical interconnections, printed circuit boards, semiconductor adhesives, casings, heat sinks, and connectors.

In sports and recreation, the combination of lightness and strength has made composites a valuable alternative to traditional materials like wood, especially in applications exposed to impacts and mechanical stress. Rackets, clubs, hockey sticks, bows, sailboats, and surfboards are among the most common applications.

In the chemical industry, composites' ability to withstand fire, chemical agents, and harsh environments makes them ideal for use in industrial plants, gratings, scrubber towers, pumps and reaction columns.

Finally, construction and home-related sectors also benefit from the advantages of composite materials. [3]

1.3. Global Market Size and Trends

The composite materials sector represents one of the most dynamic areas of the global manufacturing industry, with sustained growth in both volume and economic value. The global market recorded significant expansion, reaching a consumption of approximately 12.7 million tonnes in 2022, with an estimated value of 41 billion dollars for raw materials alone, which corresponds to over 105 billion dollars in finished components [4]. These figures confirm a growth trend that began in the 1960s, interrupted only by cyclical events such as the Covid-19 pandemic- which caused a temporary contraction in 2020, followed by a rapid recovery.

As shown in *Figure 1*, the geographic distribution of composite material consumption highlights Asia's dominance with 47% of the volume and 37% of the market value, followed followed by North America (29% by volume, 34% by value) and the EMEA region- Europe, the Middle East, and Africa- with shares of 24% in volume and 29% in value. This distribution highlights that, although Western regions register lower volumes compared to Asia, they maintain a high concentration of high-technology production and, consequently, greater added value- especially in the aerospace, defense, and advanced energy sectors.

Forecasts for the period 2022–2027 indicate sustained but geographically differentiated growth. China, alone responsible for 59% of the Asian market, is expected to drive the continent's expansion with an average annual growth rate of 4%, despite a slowdown in the construction sector. North America will benefit from public infrastructure investments, with an estimated growth rate between 3% and 4%, while Europe will continue to play a crucial role in innovation, albeit with more moderate growth (1–2% per year), particularly driven by the transportation and sustainable mobility sectors.

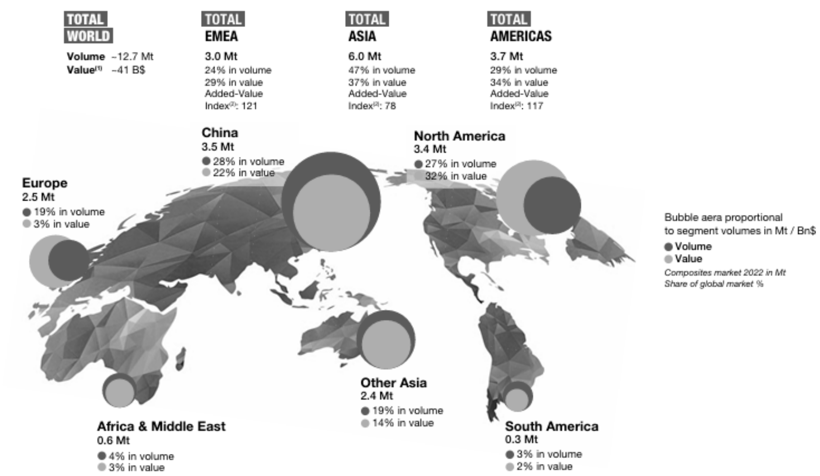

Figure 1-Geographic distribution of composite materials market in 2022. [4]

From a sectoral perspective, the evolution between 2019 and 2022 has shown heterogeneous dynamics. The energy sector experienced the most significant growth (+40%), driven by the expansion of wind energy and the revitalization of infrastructure for the extraction and distribution of hydrocarbons. Other sectors, such as electronics and marine, recorded positive developments (+8%), while construction and consumer goods recovered more slowly. In contrast, transportation and aerospace faced significant declines (respectively −16% and −45%) during the pandemic period, although they continue to play a strategic role in the long term.

Technologically, the market is characterized by a wide variety of production processes- including manual lay-up, infusion, pultrusion, filament winding, prepreg, and injection molding- adapted to specific application requirements. Thermoplastic materials, in particular, have gained ground in recent decades, now representing approximately 40% of the resin market, thanks to their recyclability, greater environmental resistance, and lower costs compared to thermosetting materials. With respect to reinforcement fibers, glass fibers remain dominant (over 90% by volume), while carbon fibers- though much more expensive- are employed in high-tech contexts, consolidating a niche segment that is steadily expanding. [4]

In summary, the composite materials market is distinguished not only by its size and geographical diversification but also by its strategic relevance in the context of technological, energy, and environmental transformations. Its future will increasingly depend on the ability to integrate innovations in both materials and production processes, with a growing focus on sustainability and the circular economy.

1.4. Limitations and Possible Solutions

Despite their numerous advantages, the widespread adoption of composite materials is still hindered by several technological and economic limitations. Traditional manufacturing processes- such as Resin Transfer Molding (RTM) or compression molding- require strict thermal cycles, expensive equipment, and prolonged production times [6]. In particular, extensively used thermosetting materials pose challenges due to their limited recyclability, complicating the integration of composites within a circular economy framework [5].

Similarly, the production of molds for composite lamination- typically achieved through subtractive methods like CNC milling on metal, wood, or other composite models- faces additional challenges. These include long fabrication times, difficulties in modifying design geometries, and high costs associated with creating custom molds. Such issues are particularly critical in sectors where customization and low-volume production are essential, for example in biomedical, motorsports, and aerospace industries.

In response to these issues, Additive Manufacturing (AM) technologies are emerging as promising solutions. 3D printing enables the creation of preforms, cores, or molds while significantly reducing production time and costs, offering greater geometric flexibility, often unattainable with traditional techniques [5]. Recent studies, including the research conducted at Universidad Politécnica de Madrid by Muñoz-Guijosa et al. [7], highlight how the use of 3D-printed molds for fiber composite lamination represents an effective alternative for producing highly personalized biomedical devices. This approach streamlines the manufacturing process, lowers production costs, and enhances the mechanical properties of final products, making them more durable and high-performing compared to traditional solutions.

1.5. Motivations and Phases of the Experimental Work

In light of the observations presented above, this thesis aims to critically explore the potential of Additive Manufacturing (AM)- with particular reference to polymer-based 3D printing using Digital Light Processing (DLP)- as an innovative alternative to the traditional production of molds for the lamination of carbon fiber-reinforced composite materials.

The main objective is to demonstrate, through an experimental approach, the technical and economic validity of this solution by emphasizing its benefits in terms of reduced production times and costs, increased design flexibility, and improved efficiency in prototyping and customization processes.

To test this hypothesis, the work is structured around two representative case studies, selected to reflect different design, dimensional, and functional requirements:

— **Case 1:** A personalized facial orthotic mask for the biomedical sector, designed to meet high ergonomic standards and to optimally adapt to the patient's facial morphology;

— **Case 2:** A central body pillar (B-pillar), a critical structural component in the automotive sector, whose design requires strict compliance with mechanical strength and dimensional precision.

The experimental process is divided into six integrated phases:

— *Digital Design*: The use of advanced CAD modeling software (including Maya and Siemens NX) to design the molds, with particular attention to the functional requirements and the constraints imposed both by the printing technology and by the subsequent lamination phase;

— *Material Selection for Mold and Prepreg:* This phase involves selecting the most appropriate materials for both the mold and the prepreg;

— *Mold Fabrication*: Production of molds using 3D printing based on Digital Light Processing (DLP) technology, employing engineering-grade polymer resins capable of withstanding the thermal and mechanical stresses typical of the autoclave curing process;

— *Unfolding*: a digital development phase on the computer, which consists of transforming the three-dimensional geometry of the mold into a two-dimensional representation, necessary to facilitate the subsequent application and placement of the prepreg during lamination;

— *Lamination*: Manual application of prepreg materials following predefined lay-up sequences;

— *Autoclave Curing*: Subjecting the laminated components to an autoclave curing cycle to achieve complete and controlled polymerization;

— *Critical Analysis of the Results*: Comparing the obtained data with the preset performance targets and discussing the application limits of the experimental approach.

This study is part of a broader research and development effort aimed at digitizing manufacturing processes within the composite materials sector, promoting a transition toward more flexible, and integrated production models. The use of AM in early production phases- such as prototyping and tooling (molds and fixtures)- represents one of the most promising frontiers, especially in contexts where customization, geometric complexity, and rapid design iteration are key competitive factors.

Thus, this thesis intends to provide a substantive contribution to the evaluation of the operating conditions and applicability limits of this technology in the context of advanced composites, helping to define strategies for effectively integrating additive manufacturing into traditional workflows. In doing so, it aims to support the development of agile, scalable production models that are innovation-driven and aligned with the challenges posed by high-tech industrial sectors.

2. State of the Art

This chapter introduces the main manufacturing techniques for Carbon Fiber Reinforced Polymers (CFRP), focusing on the fundamental principles behind each process.

Conventional fabrication methods are discussed, including open-mold and closed-mold processes, with an emphasis on prepreg lay-up and curing in autoclave. Advanced and automated techniques are also examined, highlighting their potential to improve production efficiency, reduce costs, and enable higher design complexity. Key process parameters, material choices, and typical application domains are outlined to provide a comprehensive overview of the current state of the art.

2.1. Definition and Classification of Composite Materials

In the course of the analysis, it is useful to focus on the main categories into which composite materials can be classified based on the chemical and physical nature of the matrix. Although their definition and structural peculiarities have already been discussed in the introductory paragraphs, it is worth reiterating that the mechanical and functional performance of a composite material derives not only from the presence of a reinforcing phase but also from the characteristics of the matrix that hosts it. The matrix, in fact, not only ensures the cohesion of the system and the transmission of loads but also plays a fundamental role in resisting environmental agents and in the overall thermomechanical response of the composite.

Based on this criterion, composite materials are generally distinguished into three macro-classes:

- Polymer Matrix Composites (PMCs) are the most widely used class, due to their low density and ease of processing at relatively low temperatures. This category includes thermosetting matrices (such as epoxy and vinyl ester resins) and thermoplastic matrices (such as PEEK and PPS), combined with fibrous or particulate reinforcements. PMCs are extensively employed in the aerospace, automotive, and sports sectors, as well as in the fabrication of high-performance laminated structures. The CFRPs (Carbon Fiber Reinforced Polymers) analyzed in this study belong to this category [1][2];
- Metal Matrix Composites (MMCs), in which the continuous phase is a metal (typically aluminum, magnesium, or titanium), are distinguished by their excellent thermal conductivity and mechanical strength at elevated temperatures. These composites are

used in advanced applications requiring good fatigue and wear resistance, such as structural components in the automotive and aerospace industries [1];

— Ceramic Matrix Composites (CMCs), finally, are designed to operate in extreme environments, such as high temperatures and corrosive atmospheres. Although they exhibit lower toughness compared to the other classes, CMCs offer superior resistance to oxidation, chemical stability, and creep resistance. They are employed in turbines, nuclear reactors, and thermal protection systems [2].

In addition to the matrix type, the morphology and nature of the reinforcement significantly influence the behavior of the composite material and lead to further subclassifications. Reinforcements may be continuous or discontinuous, fibrous, particulate, or laminar; among these, continuous oriented fibers are most commonly used in structural composites, as they enable tailored mechanical performance aligned with the expected load paths [1].

2.2. Mechanical Properties and Advantages of CFRP

This study focuses specifically on CFRPs, which consist of thermosetting polymer matrices- epoxy resins, in the specific case studies- reinforced with continuous carbon fibers. These materials represent one of the most advanced and high-performance solutions in the domain of structural composites, thanks to their high specific strength, stiffness, thermal stability, and low density.

Compared to conventional metallic materials, CFRPs offer a particularly advantageous combination of mechanical properties. For instance, the specific strength (σ/ρ) of CFRPs can reach up to 875 kN·m/kg, compared to 143 kN·m/kg for steel and 148 kN·m/kg for lightweight alloys. Similarly, their specific modulus (E/ρ) can reach 125 MN·m/kg, as opposed to typical values of 27 MN·m/kg for steel and 29 MN·m/kg for light alloys [2]. These values highlight the exceptional structural behavior of CFRPs in applications where mass reduction and high mechanical performance are essential design requirements.

The selection of CFRPs as the laminating material is further justified by their excellent dimensional stability at high temperatures, attributable to the low coefficient of thermal expansion of carbon fibers [1][6].

2.3. Manufacturing Processes for CFRP Components

The production of fibre-reinforced polymer matrix composites, particularly CFRPs, can be achieved through a wide variety of manufacturing processes, each of which is tailored to specific requirements in terms of part geometry, production volume, performance, and industrial cost. The choice of the manufacturing method is therefore a critical design decision, as it directly influences the final characteristics of the component, such as void content, matrix homogeneity, fibre orientation, surface finish, and dimensional repeatability.

Manufacturing techniques are generally divided into two main categories, based on the configuration of the mold during the production process. Open moulding processes involve the exposure of the composite surface to the ambient environment during fibre placement and resin impregnation. These methods are characterised by simple tooling, low equipment cost, and good flexibility for low-volume production. However, they may result in greater variability in void content, lower dimensional control, and reduced surface quality.
Closed molding processes, on the other hand, involve enclosing the composite material entirely between two mold surfaces, often under vacuum or applied pressure. This setup improves dimensional repeatability and ensures superior surface finish. These processes are typically preferred for high-performance components and medium- to high-volume production. [1]

Within the scope of this thesis, it is important to review the most relevant traditional manufacturing methods, in order to justify the selection of the prepreg-autoclave route adopted in the project.
The selected methods for comparison include:

— Hand lay-up and vacuum bagging – manual open molding with vacuum assistance;

— RTM (Resin Transfer Molding) – closed molding with resin infusion;

— Filament winding – automated winding for axisymmetric geometries;

— Pultrusion – continuous process for constant cross-section profiles;

— Compression molding and SMC/BMC – high-pressure moulding for industrial-scale production;

— Prepreg with autoclave curing – advanced thermopressure method, investigated in detail in the case study.

-Filament winding

The principle of the filament winding process lies in the controlled placement of continuous rovings- composed of thousands of filaments- impregnated with a thermosetting resin onto a rotating mandrel (see *Figure 2.a*). The fibre deposition can occur in two main modes: through in-line impregnation with liquid resin, known as *wet winding*, or by using pre-impregnated rovings (*prepreg*). The fibres are placed at specific angles, selected according to the load conditions expected on the final component. The winding angle, governed by the relative motion between the mandrel and the delivery system, determines the primary direction of laminate strength and can vary from values close to the axial direction (e.g., ±15°) up to fully circumferential paths (90°) (see *Figure 2.b*) [1].
Upon completion of deposition, the component undergoes a thermal curing cycle in an oven, which allows full cross-linking of the matrix. The inner mandrel may be made of metal, polymeric or fusible material, and is designed to be removed after curing if it is not part of the final structure. The choice of mandrel also plays a decisive role in determining the internal surface finish and dimensional accuracy of the component [6][8].
The quality of the final product is influenced by several critical factors, including the tension applied to the fibres during winding- which must be low enough to avoid mechanical damage to the filaments but sufficient to ensure compaction; the uniformity and control of the resin content, which directly affect residual porosity; and the precision in managing the winding angles, which impacts the homogeneity of the laminate and its mechanical response under load [1].

Among the main advantages of this process are its high level of automation- enabling highly repeatable production- and the ability to achieve high fibre volume fractions, typically above 60%, with accurate alignment in the designed load directions. These features translate into excellent specific mechanical performance, particularly in the axial and hoop directions [6]. Moreover, the automated nature of the process makes it suitable for both series production and the manufacturing of large components, with deposition rates that can exceed 180 kg/h [8].

However, filament winding also presents certain limitations. The process is almost exclusively applicable to axisymmetric geometries or those with continuously varying cross-sections, and is unsuitable for the production of components with concave surfaces or complex shapes. Additionally, the outer surface finish of the part is often inferior to that obtained by other closed-mold processes, due to the absence of external confinement during deposition and curing, which may necessitate post-processing steps where tight dimensional tolerances or high surface quality are required [6][1].

Despite these constraints, the process remains a highly efficient and well-established technology for the production of structural composite components subjected to predominant longitudinal and transverse loads, such as compressed gas cylinders, cryogenic tanks, and fuel containers for aerospace applications [8].

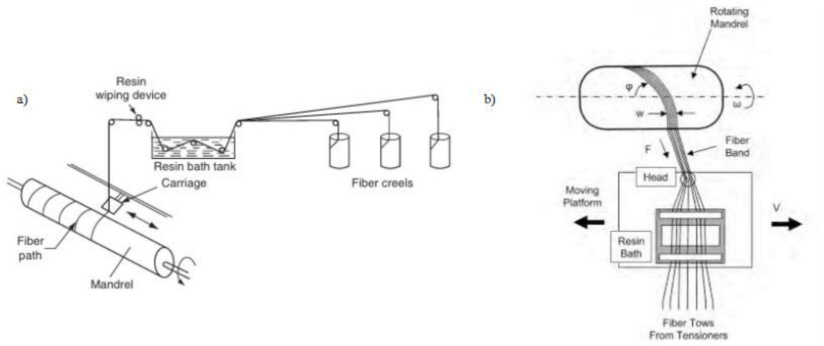

Figure 2- Filament winding process [9][6]

-Poltrusion

Pultrusion is a continuous and automated manufacturing process designed for the high-productivity fabrication of fiber-reinforced composite profiles with a constant cross-section. The term derives from the combination of *"pull"* and *"extrusion"*, clearly indicating the core principle of the method: the continuous pulling of reinforcing fibers through an impregnation system and a heated die that shapes and cures the final composite part [1][6]. The process begins with continuous fiber rovings- typically glass or carbon- drawn from creels and guided into a resin bath, where they are impregnated with low-viscosity thermosetting resins such as polyester, vinyl ester, or epoxy. After the excess resin is removed, the impregnated fibers pass through a preforming stage to align and compact the reinforcement. They are then pulled into a heated die that has the final desired cross-sectional shape. The resin cures through a combination of external heating and the exothermic reaction of the matrix system. Once fully polymerized, the cured profile is pulled by a clamping or belt-driven system and finally cut to the required length by a saw synchronized with the continuous motion. [6]. A schematic representation of the pultrusion process is shown in *Figure 3*.

Due to its continuous nature, pultrusion is highly efficient and allows for production speeds ranging from 10 to 200 cm/min, depending on the geometry of the part and the reactivity of the resin. Fiber volume fractions exceeding 60% can be achieved, resulting in excellent mechanical properties in the longitudinal direction [1]. The process is particularly suitable for manufacturing structural elements such as rods, beams, flat panels, C- or U-channels, and tubular profiles, as long as the cross-section remains constant along the entire length.

The main advantages of pultrusion include low labor costs, high automation, minimal material waste, and excellent consistency in mechanical performance. It is especially well-suited for high-volume production of linear components used in construction, transportation, and increasingly in aerospace applications [6].

However, pultrusion also has some limitations. The requirement for a constant cross-section rules out the fabrication of complex or tapered geometries. Moreover, the fiber orientation is predominantly unidirectional, which may limit transverse strength unless supplemented with mats or woven fabrics. Surface finish quality depends on resin shrinkage during cure and the manufacturing accuracy of the die. Setup times are also significant, making the process economically viable mainly for large-scale production [1][6].

In summary, pultrusion is a mature and well-established technique for industrial-scale manufacturing of linear composite profiles, best suited to standardized production rather than customized or geometrically complex components.

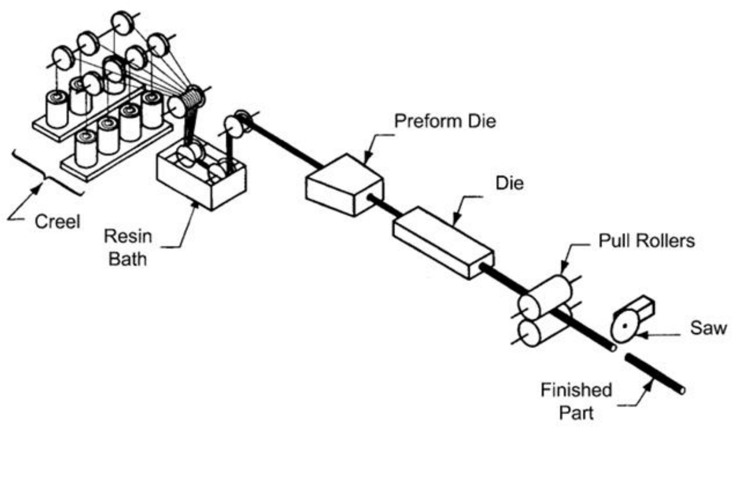

Figure 3-Poltrusion process [6]

- Hand lay-up

The hand lay-up process is one of the most historically established and simplest techniques for the fabrication of laminated composite materials. It involves the manual placement, layer by layer, of reinforcing fabrics- typically glass, carbon, or aramid fibers- into an open mold, followed by the application of a low-viscosity thermosetting resin, such as epoxy, polyester, or vinyl ester. The resin is manually distributed using rollers or spatulas to ensure uniform infiltration into the reinforcement. Once the lay-up is completed, the composite is left to cure either at room temperature or under controlled thermal conditions, depending on the resin–hardener system employed (see *Figure 4*) [3].

A critical aspect of the process is the mold, which is generally made of metal (aluminum or steel) to ensure repeatability and durability. However, for low-volume productions, more economical materials may be used, such as plaster, wood, resins, or even structural composite materials. The choice of mold material depends on the expected number of production cycles, the curing temperature, and the dimensional accuracy required [6].

An extension of the process is represented by *vacuum bagging*, a technique aimed at enhancing the quality of the laminate and reducing defects such as air entrapment or resin-rich areas. This variant involves covering the lay-up with a plastic membrane sealed around the mold edges and connected to a vacuum system. The vacuum exerts uniform pressure on the component, promoting fiber compaction, air evacuation, and homogeneous matrix distribution.

Despite its low complexity and minimal initial investment, the hand lay-up technique is significantly influenced by operator skill. For this reason, although it offers notable flexibility, it is less suited for large-scale production. It remains highly relevant for the manufacturing of single parts, highly customized components, and for the fabrication of molds and positioning jigs in craft or semi-industrial settings. The technique is still successfully used in the marine, sports, biomedical, and aerospace sectors, particularly in applications where customization is prioritized over productivity [6][8].

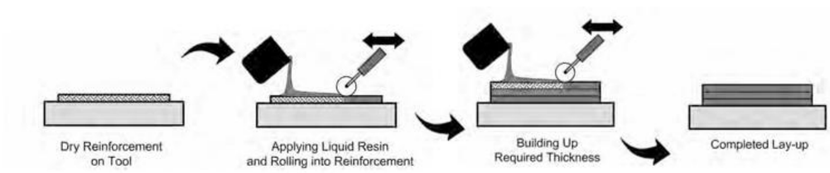

Figure 4-and lay-up process. [6]

-Resin Transfer Molding

Resin Transfer Molding (RTM) is a closed-mold manufacturing process widely used for the production of fiber-reinforced polymer composite components characterized by complex geometries, high mechanical performance, and superior surface finishes. The process involves placing a dry fiber reinforcement- typically preformed- into a rigid mold composed of two matched halves, which is then sealed and subjected to the injection of a low-viscosity thermosetting resin, often under vacuum or low pressure. The resin is introduced into the mold cavity through a network of specifically designed channels, allowing for uniform impregnation of the reinforcement until the cavity is fully filled (see *Figure 5*) [6].

Once impregnation is complete, the mold is maintained at controlled thermal conditions to enable complete curing of the polymer matrix. The use of a closed mold allows for accurate dimensional control and high surface quality on both sides of the final part, often eliminating the need for post-processing.

Among the main advantages of RTM are reduced emissions of volatile organic compounds (VOCs), high process repeatability, good laminate quality, and the potential for industrial automation. These characteristics make the process well-suited for medium-scale production runs. However, several critical factors must be managed: careful design of the fiber preform and resin distribution network is essential, as is control over resin viscosity and reactivity. Failure to properly address these aspects may lead to defects such as porosity, incomplete impregnation, or dry spots, which significantly compromise the final product quality [10].

A further limitation is related to mold cost. RTM molds must be designed to withstand repeated thermal cycles and moderate pressures, and are typically manufactured from metal or high-stiffness composite materials with tight geometric tolerances. These requirements make RTM less competitive for low-volume production or rapid prototyping when compared to more flexible fabrication methods [6].

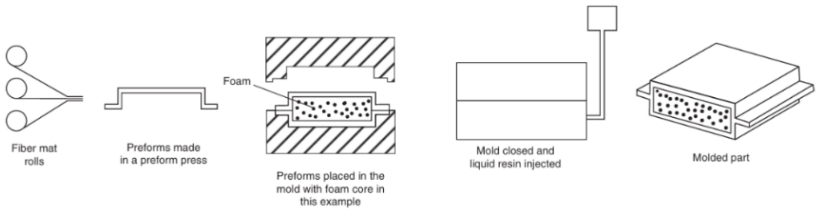

Figure 5- RTM process. [9]

-Compression molding

Compression molding is one of the most established hot-forming techniques in the composite materials industry, particularly well-suited for high-volume production of

components with complex geometries, high mechanical performance, and reduced cycle times [3]. (*Figure 6*) The process involves the use of a heated, closed mold, typically made of metal, into which a reinforced compound- usually in the form of Sheet Molding Compound (SMC) or Bulk Molding Compound (BMC)- is placed and compressed at elevated temperatures until full polymerization of the matrix is achieved. The composite material is distributed within the mold cavity, where mechanical pressure (typically between 5 and 20 MPa) and controlled temperature (usually ranging from 120 °C to 180 °C) ensure complete conforming and curing of the part in just a few minutes. The precision of the mold enables the production of components with tight dimensional tolerances and high surface quality, minimizing the need for secondary machining operations [8].
SMC and BMC differ in both their physical form and the method of placement into the mold. SMC is supplied as a sheet composed of resin pre-impregnated with chopped fibers (commonly glass), fillers, and additives, which can be cut and shaped to fit the mold geometry. BMC, in contrast, is a more viscous, dough-like material that can be deposited manually or via automated systems. Both allow for the manufacture of complex parts, including the integration of metallic inserts, and are widely used in the automotive, electrical, and industrial sectors.

Among the main advantages of compression molding are fast cycle times, dimensional repeatability, automation potential, and geometrical versatility, making it highly suitable for the fabrication of technical components, covers, housings, and lightweight structural parts. However, the technology requires highly engineered molds- which are costly- and careful process design, particularly in terms of thermal cycles and material dosage. These factors limit its feasibility primarily to industrial-scale manufacturing [6][8].

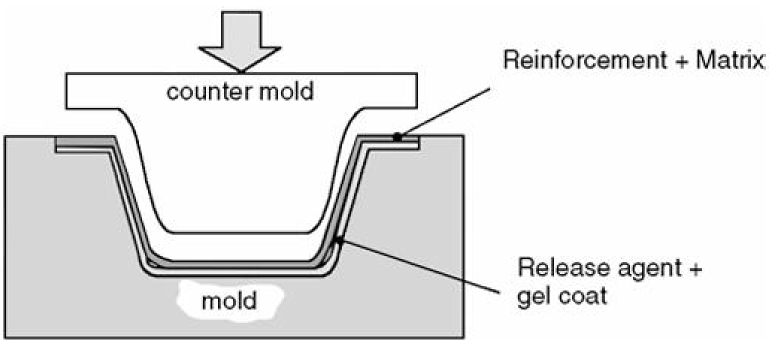

Figure 6-Compression molding process. [6]

- Prepreg with autoclave curing

The prepreg lay-up and autoclave curing process represents one of the most advanced and high-quality manufacturing methods for producing high-performance composite materials. It is based on the use of prepregs- fiber reinforcements, typically carbon, glass, or aramid fibers, pre-impregnated with a partially cured thermosetting resin (B-stage)- which ensure precise control of resin content and excellent homogeneity between layers [1][8]. The lay-up of the laminate is carried out manually or via automated systems, layering the prepreg sheets over a male or female mold made of materials capable of withstanding the high temperatures and pressures involved in the process [4]. Once the lay-up is complete, the laminate stack is covered with auxiliary materials (release films, breather fabric, barrier films) and sealed within a vacuum bag. (*Figure 7.a*)

The assembly is then placed in an autoclave (*Figure 7.b*), where it undergoes a controlled thermo-pressurized curing cycle. The vacuum removes residual air and volatiles, while the combined action of elevated temperature (typically between 120 °C and 180 °C) and applied external pressure (up to 0.7 MPa) promotes laminate compaction and complete crosslinking of the polymer matrix. The result is a composite with very low void content (below 1%), outstanding mechanical properties, high-quality surface finish, and excellent dimensional repeatability [6].

Although the process is time- and cost-intensive- especially due to the need for high-end infrastructure such as autoclaves, vacuum systems, and high-performance molds- it remains the benchmark for the production of critical structural components in aerospace, high-performance automotive, advanced sports equipment, and, more recently, biomedical applications, where strict requirements on reliability, laminate integrity, and dimensional tolerances are imperative [1].

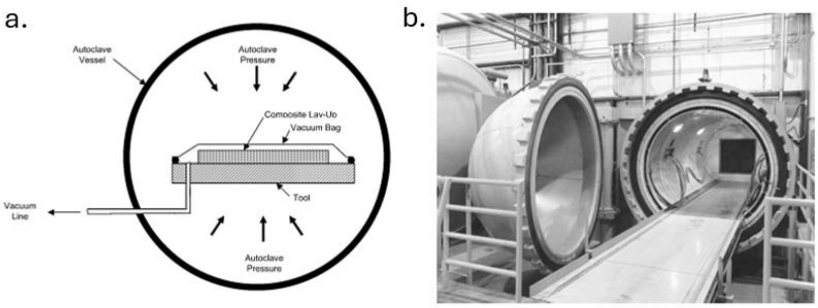

Figure 7- (a) Prepreg lay-up and vacuum bagging setup. (b) Industrial autoclave used for composite curing. [6]

A review of the main manufacturing methods for CFRPs shows that each process addresses specific design and production requirements- such as part geometry, production volume, mechanical performance, and industrial cost. Techniques like hand lay-up and vacuum bagging offer flexibility and low initial investment, but rely heavily on operator skill and are limited in terms of automation and repeatability. In contrast, processes like pultrusion and filament winding are highly automated and efficient, though restricted to simple, repetitive geometries and offer limited adaptability for customized parts.

More advanced methods, such as Resin Transfer Molding (RTM) and compression molding, strike a balance between productivity and surface quality. However, they demand significant investment in tooling and require careful process design, making them less suitable for small-scale production or prototyping. Prepreg lay-up combined with autoclave curing remains the state-of-the-art solution for manufacturing high-performance structural components. While it entails longer processing times, higher costs, and the need for specialized infrastructure, it offers unmatched laminate quality, mechanical properties, and dimensional accuracy.

Given these considerations, this thesis adopts prepreg lay-up with autoclave curing as the reference process, as it represents the industrial benchmark for high-performance composite components. This method aligns closely with the objectives of the study, which aims to explore the compatibility between this advanced process and polymeric molds produced via 3D printing.

The experimental protocol has therefore been designed to evaluate the technical feasibility of this approach, with particular focus on the mechanical and thermal stability of the printed molds, as well as on the structural integrity of the final laminate. The broader goal is to demonstrate how additive manufacturing can reduce the time and cost associated with traditional mold fabrication, while still being compatible with high-performance composite processing. The experimental results presented in the following chapters will serve as a foundation for validating this potential integration.

2.4. Additive Manufacturing: General Principles and Process Classification

Additive Manufacturing (AM), also known as 3D printing, encompasses a set of production technologies based on the controlled addition of material, layer by layer, to create three-dimensional objects from a digital model. This paradigm clearly differs from traditional subtractive or forming processes, offering greater geometric freedom, significant waste reduction, advanced customization potential, and optimized production times [11].

According to the ISO/ASTM 52900:2021 standard, Additive Manufacturing is defined as "a process used to build three-dimensional objects by adding material successively based on a digital model" [12].

The standard AM workflow consists of several fundamental stages: CAD design, conversion of the file into STL format, slicing (i.e., dividing the model into layers), additive fabrication, and post-processing.

The ISO/ASTM classification identifies seven main categories of AM technologies, differentiated by the type of material used, deposition mechanism, and energy source. Below is a brief description of the key characteristics of each category:

— *Material Extrusion (ME)*: Includes processes such as Fused Deposition Modelling (FDM), where a thermoplastic filament is heated and deposited layer by layer through a moving nozzle. This is a cost-effective technology suitable for prototyping and for use with filled materials, though it has limitations in terms of resolution, interlayer adhesion, and surface finish [11].

— *Vat Photopolymerization (VP)*: Encompasses technologies such as Stereolithography (SLA) and Digital Light Processing (DLP), which use photosensitive liquid resins selectively cured by UV light or digital projection. These processes are characterized by high resolution, surface quality, and geometric precision but require post-curing and are limited to photopolymer materials [13][14].

— *Powder Bed Fusion (PBF)*: Involves the selective melting or sintering of powdered materials (metallic or polymeric) using an energy source such as a laser or electron beam. Technologies like Selective Laser Sintering (SLS) and Selective Laser Melting (SLM) allow for the production of high-performance functional components, although they require thermally controlled environments and highly complex machinery [11].

— *Material Jetting (MJ)*: Based on the deposition of droplets of photopolymeric material that are solidified using UV light. This method enables high resolution and multi-material combinations but is limited by high costs and the fragility of the printed materials [12].

— *Binder Jetting (BJ)*: Involves the deposition of a liquid binder onto layers of powder, which are then consolidated through sintering or infiltration. It is suitable for producing complex ceramic, metal, or sand components, although it requires long post-processing steps [11].

— *Sheet Lamination (SL)*: Consists of cutting and bonding sheets of material using adhesives or welding. It is typically used for visual applications or rapid prototyping of architectural and anatomical models [12].

— *Directed Energy Deposition (DED)*: Uses an energy beam to melt metallic powders or wires directly onto the surface of a component or substrate. It is often employed for the repair of metal parts and for large-scale production [11].

This classification highlights the broad spectrum of possibilities offered by AM and the technological diversity available today. The choice of the most appropriate technology depends on multiple factors, including the required material, dimensional accuracy, mechanical and thermal performance of the final part, production costs, and process scalability.

The following chapters will focus on the technologies most commonly used in the fabrication of composite parts and molds, with particular attention to 3D printing via photopolymerization.

2.5. Key Additive Manufacturing Technologies

Among the many technologies currently available in additive manufacturing, some have established themselves more firmly due to their reliability, industrial maturity, and material availability. In particular, Fused Deposition Modeling (FDM), liquid resin photopolymerization (in its SLA and DLP variants), and Selective Laser Sintering (SLS) are today the most consolidated methods for producing polymeric and composite components, both for prototyping and functional applications [11].

For this reason, these technologies will be individually analyzed in the following sections to critically evaluate their advantages and limitations within the application context of this thesis. This comparison will provide a rational basis for the experimental choice adopted for mold fabrication.

-Fused Deposit Modeling

Fused Deposition Modeling (FDM) is based on the selective deposition of a melted thermoplastic polymer material, which is extruded through a heated nozzle and deposited layer by layer according to a sequence defined by a CAD model converted into machine code (G-code) [11].

An FDM printer consists of three main components: the extrusion system, the build platform, and a multi-axis motion system. The core of the process is the extrusion system, responsible for melting and controlled deposition of the material. During the process, show in *Figure 8*, the thermoplastic filament, generally supplied on a spool, is mechanically fed toward the hotend, where it is heated by electrical resistors until it exceeds its melting temperature. Once softened, the material is pushed through a metal nozzle which, following the path defined by the digital model, deposits it precisely layer by layer onto the build platform. The platform is often heated to improve the adhesion of the first layer and to limit thermal deformation phenomena such as warping, thereby ensuring greater dimensional stability of the finished part [15], [16].

The print head movement typically occurs along the X and Y axes, while the Z axis enables the progressive lifting of the platform or nozzle to build the three-dimensional object. Process control is managed by an electronic unit that oversees kinematics, temperature, printing speed, and material flow, ensuring layer consistency and dimensional accuracy [11], [12].

Among the main advantages of the FDM process are operational simplicity, material versatility (including PLA, ABS, PETG, TPU, and technical polymers such as PC or PA), and low equipment costs, making it a widely accessible choice for rapid prototyping and low-volume production [17]. Moreover, the open architecture of the extruder allows the use of fiber-filled composite filaments (e.g., carbon or glass fiber), although with limitations related to fiber alignment and achievable volume fraction [18].

However, the process also presents several technical limitations. Resolution is generally lower compared to other additive technologies, and surface finish tends to be rough, often requiring mechanical or chemical post-processing. Additionally, the layering introduces mechanical anisotropy, with inferior properties in the direction perpendicular to the deposited layers. Delamination, internal porosity, and differential shrinkage phenomena can compromise the dimensional quality and structural performance of the components [19].

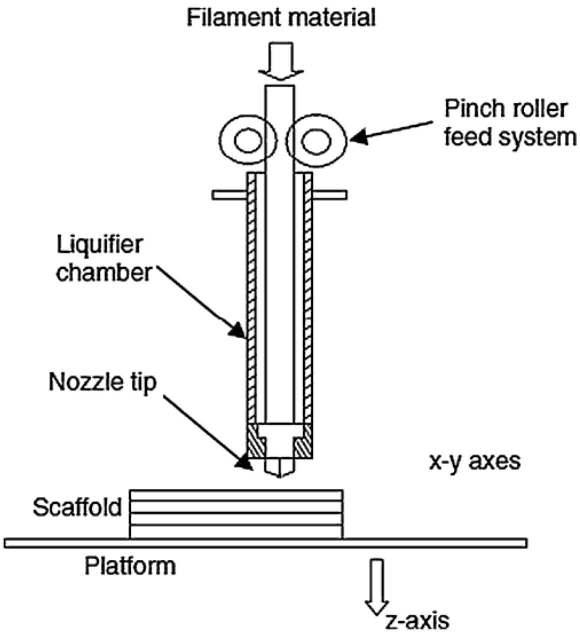

Figure 8- Schematic of extrusion-based systems. [11]

- Photopolymerization-Based 3D Printing

Photopolymerization-based 3D printing encompasses a group of additive technologies that rely on the selective curing of liquid resins through exposure to light radiation, typically in the ultraviolet spectrum. Among these, the two most established and widely used techniques are Stereolithography (SLA) and Digital Light Processing (DLP), both of which fall under the vat photopolymerization category [11] [12].

The common working principle involves the layer-by-layer photopolymerization of a liquid resin contained in a transparent vat, initiated by photochemical activation from a light source that follows geometric data extracted from a 3D CAD model [11] [17] (*Figure 9*). In the SLA process, solidification occurs via a focused UV laser beam directed by galvanometric mirrors, which traces the model's cross-section point by point on the resin surface. In contrast, DLP uses a digital projector to emit a pattern of light corresponding to an entire cross-section, allowing the simultaneous curing of the whole layer and significantly reducing printing time [16].

A third variation, often grouped with DLP due to its similar imaging approach, is Liquid Crystal Display-based 3D printing, which employs an array of UV LEDs combined with an LCD panel acting as a dynamic mask. Unlike DLP, which uses a single light projection system, the LCD method selectively blocks or transmits light through individual pixels of the screen to cure resin layer by layer. While the resolution depends directly on the screen's pixel density, LCD printers are typically more cost-effective and suitable for printing small to medium-sized components with high detail.

In all vat photopolymerization processes, the build platform moves vertically along the Z-axis, gradually lifting the printed object as new layers are formed at the base, near the optically transparent bottom of the vat [20].

The resins used are typically liquid mixtures of reactive monomers or oligomers, photoinitiators, and specific additives, with compositions varying according to the desired mechanical, thermal, and optical properties. Available formulations include standard resins, high-temperature variants, flexible, reinforced, or high-precision materials- some of which are developed specifically for advanced engineering applications with complex geometries [11] [14].

Among the main advantages of DLP compared to other additive technologies are the high resolution achievable- often below 50 μm- superior surface quality, and enhanced geometric accuracy. Furthermore, full-layer curing enables higher productivity than point-by-point scanning methods. However, photopolymer resins also present certain drawbacks: they are generally more brittle than the thermoplastics used in extrusion-based printing, often require post-curing to complete the matrix crosslinking, and must be stored in controlled environments protected from light and humidity to prevent performance degradation [16], [13].

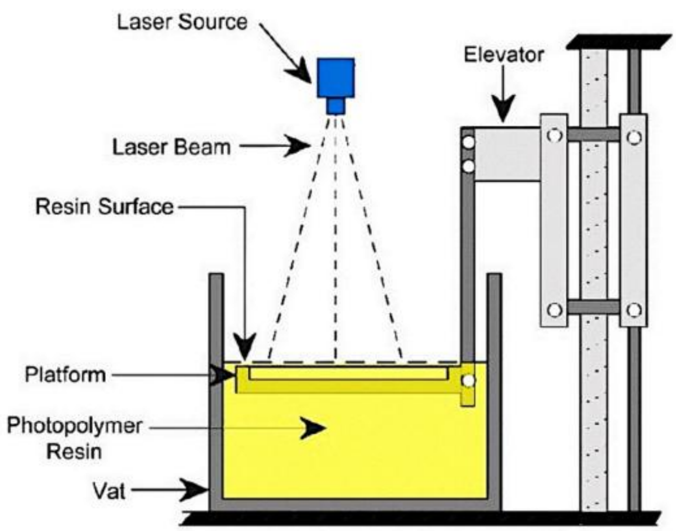

Figure 9-Schematic diagram of Vat Photopolymerization process. [20]

- ***Selective Laser Sintering***

This process relies on the selective sintering of thermoplastic powders through the use of a high-power laser, which locally melts the material according to the geometry defined by a three-dimensional CAD model. Printing takes place inside a heated chamber, maintained just below the melting temperature of the material. This condition helps reduce thermal deformation and promotes adhesion between layers [12][11].

The SLS system consists of a build chamber with a vertically moving build platform (Z-axis), a powder spreading mechanism (roller or blade), and a laser scanning unit that selectively delivers energy to sinter the desired areas. Unlike other additive technologies, SLS does not require support structures: the unsintered powder surrounding the part acts as a self-supporting medium, enabling the fabrication of highly complex geometries [11][21]. *Figure 10* show a schematic representation of the process.

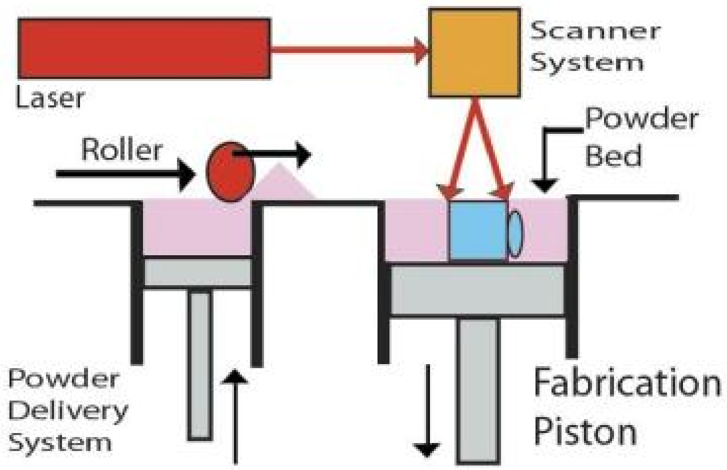

Figure 10- Schematic diagram of SLS process [22]

The materials used are typically thermoplastic polymer powders, such as polyamides, known for their good mechanical properties, dimensional stability, and chemical resistance. These materials are often available in filled versions- for example, reinforced with glass fibers or other additives- to further enhance performance. However, the resulting parts tend to have a rough surface finish and some residual porosity, which may require post-processing for aesthetic or functional applications [23].

From an economic and operational perspective, SLS involves higher costs than other additive technologies, both in terms of equipment and materials, and demands precise thermal management. Additionally, the cooling time required for the powder at the end of the print cycle can significantly extend the overall production time [16].

Based on the technical discussion of the main Additive Manufacturing technologies, it is possible to draw some guiding considerations to support the technological choice adopted for the fabrication of molds suitable for CFRP lamination.

FDM technology stands out for its economic accessibility, ease of use, and wide availability of thermoplastic materials, including fiber-reinforced filaments. Effective applications of this technique for mold fabrication in lamination processes are documented in the literature [7]. However, this technology presents some intrinsic limitations: the surface finish is generally rougher than that of other techniques, and the resolution of fine details is limited, often requiring post-processing. Moreover, the mechanical properties of the materials-although sufficient in many contexts-are generally lower than those offered by the photopolymer resins used in DLP processes, particularly in terms of stiffness, dimensional stability, and heat resistance.

Selective Laser Sintering (SLS), while offering greater design freedom and good mechanical properties through the use of high-performance polymer powders, involves higher costs and a more complex operational setup. The granular surface finish and residual internal porosity frequently require post-processing treatments to meet the functional and quality requirements of a mold.

In this context, DLP technology emerges as the most coherent solution with the objectives of this work. It enables the production of components with high resolution and excellent surface quality directly from the printing process, reducing the need for subsequent finishing. The photopolymer resins used also provide good mechanical properties and dimensional stability, making them suitable for typical requirements of manual cold or low-temperature lamination processes. Moreover, they offer sufficient thermal and chemical resistance to be compatible with autoclave curing cycles.
Finally, it should be noted that, although these considerations are supported by a technical-scientific review of the available technologies, they represent a preliminary evaluation. The actual suitability of DLP technology for mold fabrication will be verified experimentally, upon completion of the design, manufacturing, and functional validation phases.

3. Experimental Activities

As previously introduced in Chapter 1, this research explores the technical feasibility of using 3D printing- specifically Digital Light Processing (DLP-LCD)- for producing molds intended for the manual lay-up of carbon fiber prepreg composites, followed by autoclave curing.

This chapter presents the practical development of the project, detailing the methods used to design, fabricate, and evaluate the molds. These were conceived as open molds, without counter-molds, a choice aligned with the operational simplicity and flexibility required by manual laminating processes. This configuration is particularly suitable for small-scale production and rapid prototyping, especially when working with prepreg systems that involve complex thermal curing cycles [1][2].

The CAD design, lamination, and curing processes were conducted at the laboratories of the Universidad Politécnica de Madrid – Escuela Técnica Superior de Ingenieros Industriales, which provided the necessary facilities and technical support. The 3D printing phase was outsourced to 3Dtive SL, a company specializing in advanced additive manufacturing technologies based in Madrid, Spain.

The experimental workflow followed a logical sequence, starting with the characterization of materials (both for the molds and the composite), followed by digital modeling, DLP printing, manual lay-up, and autoclave curing. Each phase was applied to two case studies, allowing for a comparative assessment of the results in terms of geometric accuracy, mold performance, and quality of the final laminate.

3.1. Material Selection

The proper selection of materials is one of the key factors in the manufacturing process. The synergy between the mold material and the composite system significantly influences the final quality of the component in terms of structural integrity, dimensional accuracy, and process repeatability . In particular, in the context of high-performance prepreg lamination, it is essential that the chosen mold material ensures both thermal and mechanical stability during the autoclave curing cycle, which typically involves temperatures up to 180 °C and pressures as high as 7 bar [6]. Mold stiffness and resistance to thermal and mechanical deformation are crucial for maintaining the desired geometry and avoiding defects such as warping or surface imperfections.

At the same time, the selection of the composite material must take into account the mechanical properties of the fiber–matrix system, its compatibility with the matrix curing cycle, and its ease of processing in order to minimize defects such as delamination or porosity.

This work builds upon the methodology and experimental parameters validated by Muñoz-Guijosa et al. (2020) [7], who used Toray T700S prepreg on molds fabricated via FDM 3D printing. Their study defined an optimized autoclave curing cycle and consolidated a rapid prototyping approach. The main innovation introduced in the present study consists in the use of molds produced using DLP technology and high-temperature photopolymer resins, which offer significant improvements in geometric resolution.

The following sections provide a detailed overview of the materials selected for the mold and the composite, highlighting the key technical features and the rationale behind their choice, with reference to the properties summarized in the corresponding tables.

3.1.1. Mold Material Selection

For the fabrication of the molds, two photopolymer resins specifically developed for 3D printing technologies were selected: Phrozen TR300 Ultra-High Temp and Phrozen Ceramic Pro Resin (*Figure 11*).
The TR300 resin was chosen for its high thermal resistance (HDT 160 °C), mechanical stiffness, and favorable cost (approximately €70/kg). It is compatible with commercial DLP/LCD printers, facilitating integration into existing production workflows.
In contrast, Ceramic Pro Resin was selected for portions of the mold requiring superior thermal stability and mechanical rigidity. It contains over 70% ceramic filler, can withstand temperatures up to 280 °C, and ensures excellent dimensional accuracy. Its higher cost of around €310/kg restricts its use to critical components where maximum performance is needed.
Both resin are easily processable using commercial DLP printers, which facilitates integration into standard production workflows.
To enable direct comparison, Case Study 1- which involves a relatively compact mold- will be fabricated using both materials. Meanwhile, for Case Study 2, which requires a significantly larger mold volume, fabrication will be carried out only with the more economical TR300 resin, in order to contain material and production costs.

Figure 11-Phrozen TR300 Ultra-High Temperature on the left and Phrozen Ceramic Pro Resin on the right. [24]

The main technical properties of the selected resin are summarized in *Table 1* and *Table 2*.

Table 1- Phrozen TR300 Ultra-High Temp's Technical Properties. [24]

PROPERTY	VALUE
Technology	DLP/LCD 3D Printing
Material Type	Photopolymer Resin
Heat Deflection Temperature (HDT) at 0.45 MPa	160 °C (after 1h at 200 °C)
Main Features	Thermal stability, high stiffness, pressure resistance
Weight	1 kg per bottle
Density	1.17 g/cm³
Viscosity	123.60 cP
Surface Hardness	80 Shore D
Tensile Stress at Break	59.90 MPa
Elongation at Break	3.90 %
Tensile Modulus	3443.70 MPa
Notched Izod Impact Strength	22.10 J/m

All specifications are tested after 30 minutes of post-curing.

Table 2- Phrozen Ceramic Pro Resin's Technical Properties. [24]

PROPERTY	VALUE
Technology	DLP/LCD 3D Printing
Material Type	Ceramic-filled photopolymer resin
Ceramic content	> 70%
Heat Deflection Temperature (HDT)	280 °C
Weight	0.5 kg per bottle
Flexural modulus	10,086 MPa
Viscosity	230 cP (at 30 °C)
Density	1.65 g/cm³
Izod impact strength	18.4 kJ/m²
Tensile strength	68.4 MPa
Tensile modulus	8,325.8 MPa
Flexural strength	84 MPa
Surface hardness	Shore D > 90
Softening temperature	≈ 181.8 °C
Chemical and thermal resistance	High

3.1.2. Composite Material Selection

Given the choice of autoclave-cured prepreg as the fabrication method for the carbon fiber components, the selection of the prepreg material represented a key phase of the process.

Prepregs are composite materials consisting of reinforcing fibers pre-impregnated with a partially crosslinked thermosetting polymer matrix. This intermediate B-stage of the resin, between liquid and solid, enables an optimal balance between material workability and the final quality of consolidation. In this state, the matrix exhibits intermediate viscosity and stiffness, allowing for easy handling and the stacking of fiber layers without resin flow or deformation, which facilitates the production of components with complex geometries. It is worth noting that this partial polymerization also allows the prepreg to be stored at low temperatures, effectively inhibiting further crosslinking and thus ensuring an adequate shelf life. During the subsequent consolidation stage- typically carried out in an autoclave- the matrix completes its polymerization, achieving full crosslinking and thereby imparting the desired mechanical and chemical properties to the composite. [9]

Based on the findings reported by Muñoz-Guijosa et al. [7], a unidirectional carbon fiber prepreg (Toray T700S) impregnated with a partially cured epoxy resin was selected. The unidirectional fiber architecture is particularly suited to applications where high strength and stiffness are required primarily along one direction, making it ideal for structural components subject to directional loads. This material was validated for a curing cycle consisting of 2 hours at 120 °C, with a controlled heating ramp of 3 °C/min, ensuring good fiber–matrix adhesion and complete crosslinking.The key properties of the selected prepreg-such as areal weight, fiber type, and matrix composition- are summarized in *Table 3*.

Table 3- Toray T700S's proprieties. [7]

PROPERTY	VALUE
Fiber Type	Toray T700S (UD)
Matrix	Epoxy
Areal Weight	200 g/m²
Fiber Volume Fraction	~60%
Lamina Thickness	~0.20 mm

3.2. CAD Modeling

This section describes the geometric modelling process of the molds, developed using CAD software based on the established design specifications. The accurate definition of the 3D model is a crucial phase to ensure proper additive manufacturing and full functionality of the mold during the subsequent lamination process.

For both projects, the primary modelling tool was Autodesk Maya [25], a professional platform for 3D modelling, animation, and rendering, particularly well-suited for managing organic surfaces and complex forms. For the structural component, Siemens NX [26] was additionally used to support parametric modelling and the engineering of high-precision features.

3.2.1 Case Study 1 – Facial Orthosis Mask

A facial orthosis mask is a custom medical device designed to fit the anatomical surface of the human face, with protective, corrective, or post-surgical functions. These masks are commonly used in cranio-maxillofacial applications, where they help support soft tissues, stabilize postoperative conditions, or shield the face from external stresses, particularly after trauma or reconstructive surgery. [27]

As a starting point, a 3D STL model of a human head was imported into the Autodesk Maya workspace (*Figure 12*), sourced from the open-access platform Cults3D. [28] This file served as the geometric reference for creating a mask that would precisely conform to the facial morphology.

Two versions of the mold were developed during this case study. The first was based on the initial CAD model described below, while the second incorporated some design improvements that emerged after preliminary testing and lay-up trials. These changes were applied only to the version printed using the ceramic resin.

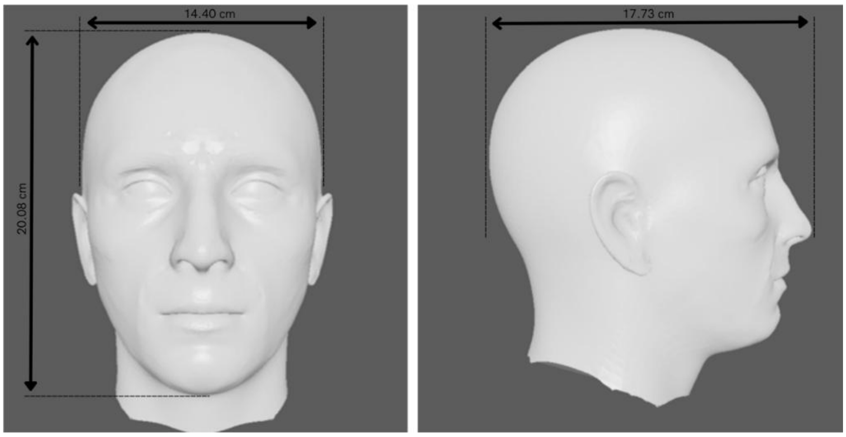

Figure 12-STL model of Human Head

The face mesh was then activated as a live surface using the “Make Live” function, allowing new vertices and edges to automatically snap to the existing geometry- an essential aid for topologically accurate surface modelling. Using the Quad Draw tool, a new mesh was manually created by sketching directly onto the face surface, closely following its contours and curvatures.

The surface was deliberately shaped to fully cover the zygomatic (cheekbone) area and partially wrap around the nasal septum, while maintaining a wide opening around the eyes to avoid obstructing peripheral vision and enhance user comfort. As shown in *Figure 13*, the resulting geometry is clean, uniform, and perfectly adherent to the underlying face model.

Once the surface onto which the lamination would be performed was obtained- modelled to perfectly adhere to the patient's facial anatomy- extrusion operations were carried out to assign a uniform thickness to the model and to generate appropriate trimming flanges.

During the design phase, a preliminary evaluation of the lamination orientation was conducted, with the aim of ensuring that the aesthetically superior face of the composite- the one smoother, more compact, and free of defects- would correspond to the inner face of the mask, intended to be in direct contact with the patient's skin. In composite laminates produced through open-mold processes followed by autoclave post-curing, it is standard practice to distinguish between two surfaces with different morphological characteristics. The face in contact with the mold typically presents a more homogeneous and regular finish, benefitting from the geometric constraint imposed by the mold and the uniform pressure applied during polymerization, which promotes efficient consolidation of the composite. Conversely, the opposite surface, not supported by a rigid counterform, may exhibit irregularities or visual imperfections, often caused by the presence of auxiliary materials- such as peel-ply, bleeder, or release films- which, while essential for process control and demolding, do not ensure comparable aesthetic quality.

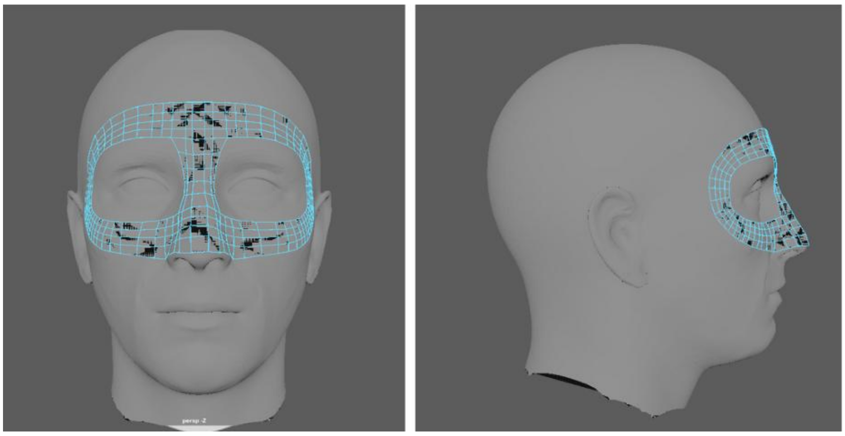

Figure 13- Quad draw sketch of the mask over the STL model of the patient's face.

Before defining the model thickness, additional peripheral borders were introduced along the edges of the mask and around the eye openings. These extensions were specifically added to create auxiliary areas that facilitate the positioning of the prepreg layers during manual lay-up. By extending the surface beyond the functional geometry of the part, they help ensure better fiber alignment at the edges, minimize the risk of defects such as fiber pull-back or delamination, and provide controlled areas where excess material can accumulate. The presence and function of these borders are clearly illustrated in *Figure 14*.

Once the peripheral borders were defined, the thickness of the model was extruded inward, so as not to alter the external geometry- namely, the surface to be used as the lamination interface. This design choice preserves the geometric accuracy of the functional surface, improving the fit and adherence of the final composite part. This strategy is also illustrated in *Figure 15*, where it is clearly visible that the volumetric growth occurs inward relative to the original surface.

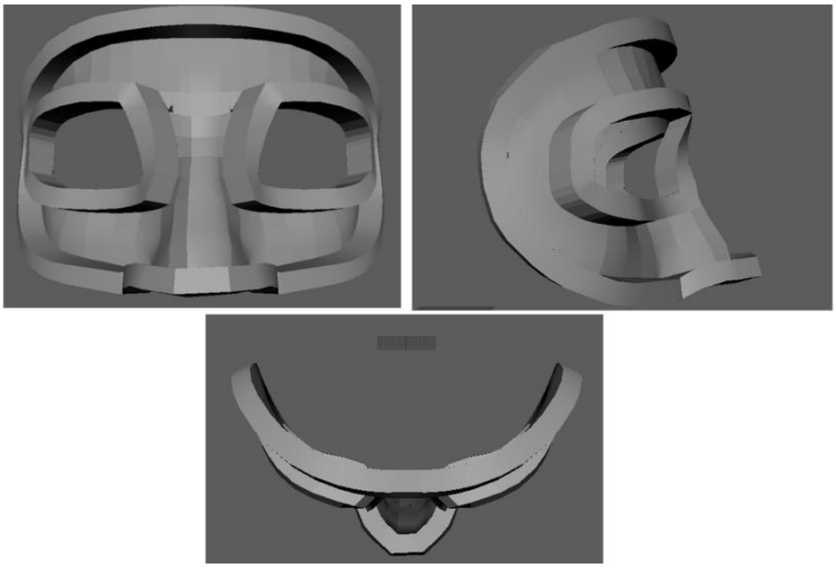

Figure 14- Intermediate CAD model of the Face Mask mold- showing the lamination surface and the extended borders designed to assist manual lay-up.

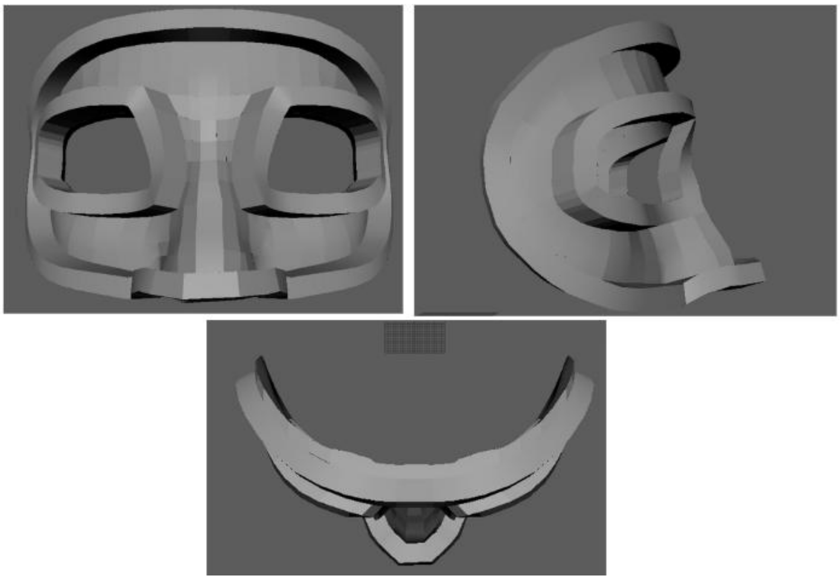

Figure 15- Intermediate CAD model of the Face Mask mold- showing the added thickness extruded inward, preserving the original external lamination surface.

The assigned thickness ensures the structural rigidity necessary to withstand the mechanical and thermal stresses generated during the autoclave curing cycle, particularly those related to thermal gradients and isostatic pressure.

To further support the demolding process, three draft angles were integrated into the design (*Figure 16*). These allow for easy removal of the laminated part from the mold after curing. Beveled edges were applied to both the trimming flanges and the draft transitions.

Finally, smoothing and triangulation operations were applied to the entire model. The smoothing process was essential to increase the curvature continuity of the surfaces, eliminating sharp edges and transitions that could compromise both the quality of the 3D print and the performance during lamination. Obtaining a continuous and regular surface reduces the risk of localized fiber distortions or defects during the lay-up of composite layers. Subsequently, triangulation ensured that the mesh structure was fully compatible with the STL format. Triangulated meshes prevent issues related to non-planar polygons during slicing and printing, ensuring better fidelity of the geometry and minimizing the occurrence of printing artifacts. Together, these operations provided a geometrically clean and functionally optimized model for the subsequent production phases.

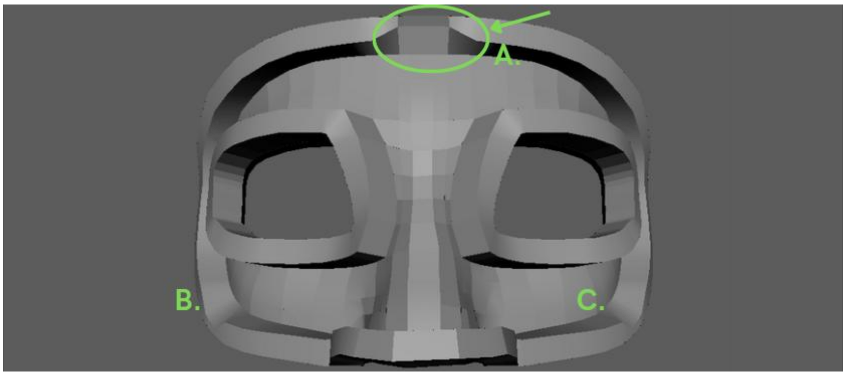

Figure 16- Intermediate CAD model of the Face Mask mold- highlighting the introduction of draft angles to facilitate demolding.

The mold corresponding to Mask A- TR300-based version- is shown in *Figure 17*.

Following initial testing, two key design modifications were introduced in the second version of the mask. First, the size of the peripheral borders along the edges of the mask and around the eye openings was reduced. In the initial model their large diameter made demolding difficult. The updated design reduced their dimensions while still ensuring functional effectiveness, thus simplifying removal of the cured part.

Second, the peripheral border along the edges of the mask which were originally perpendicular to the main surface, were modified to feature a slight outward inclination. This adjustment facilitated both the manual lay-up of the prepreg and the demolding process, minimizing stress concentrations at the edges and improving the overall quality of the final composite.

These modifications, show in *Figure 18*, were implemented in the mold printed using both material selected, allowing a direct comparison between the initial and improved designs under consistent processing conditions.

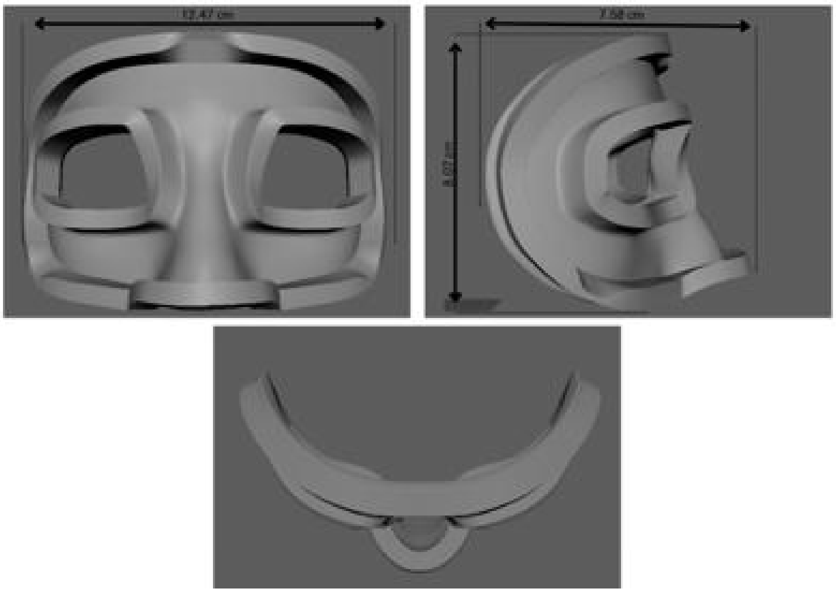

Figure 17- Final CAD model of the Face Mask mold- VERSION A.

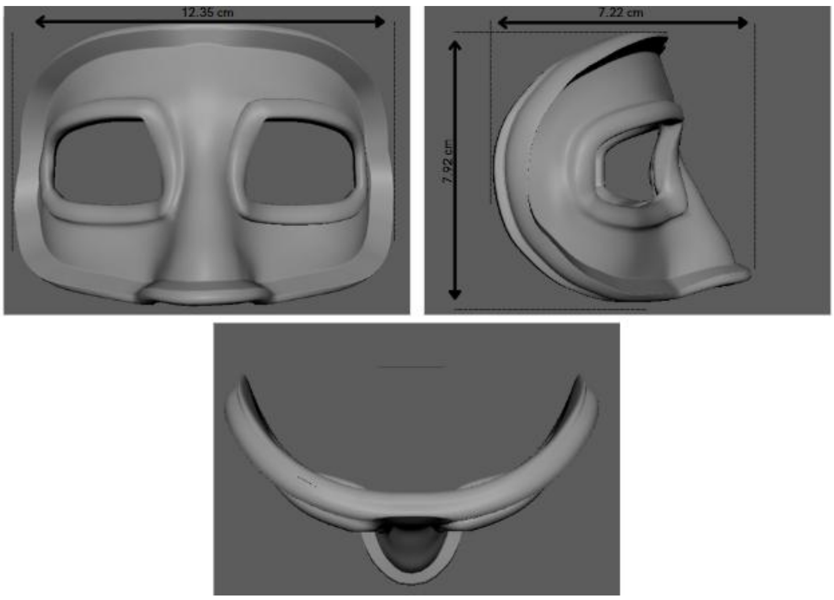

Figure 18- Final CAD model of the Face Mask mold- VERSION B.

3.2.2. Case Study 2 – Car B-Pillar

The second case study focuses on the design of a mold for the lamination of a car B-pillar, a structural component located between the front and rear doors of a vehicle. (*Figure19*)

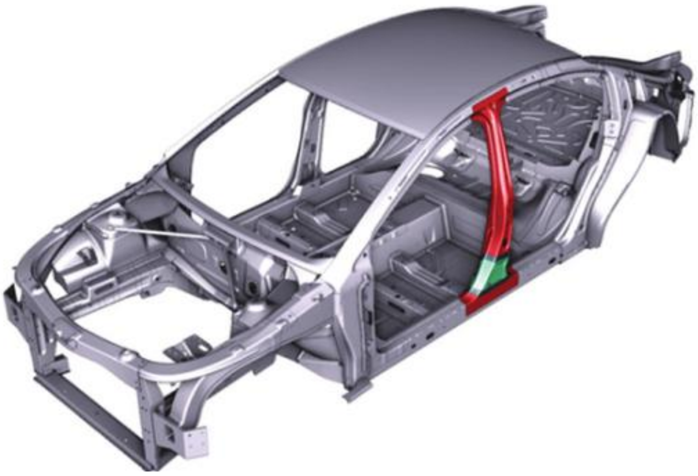

Figure 19-Geometric reference of the B-pillar. [29]

The starting geometry (*Figure 20*) was obtained as an STL file from an open-access online source. [30]

It is important to note that the model used was not an industrially certified or validated CAD file. Instead, its selection was deliberate: the aim of this thesis is not to reproduce a specific commercial automotive component, but rather to assess whether a mold generated from a non-verified geometry can still meet the geometric and mechanical requirements necessary for successful composite lamination.

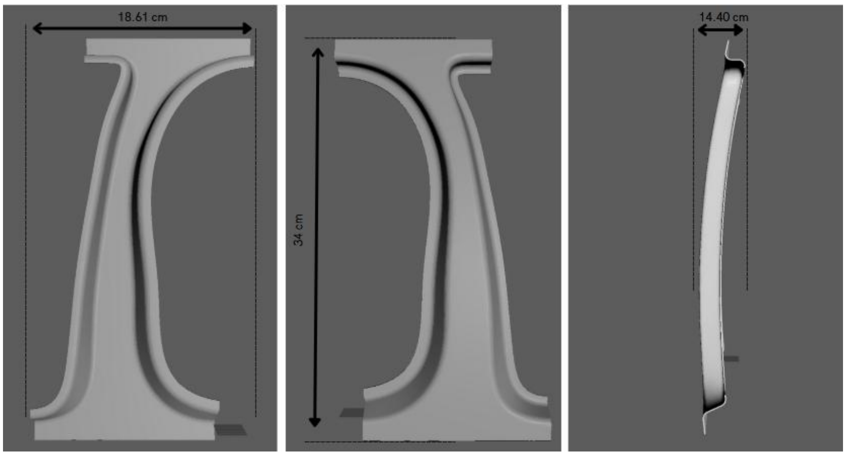

Figure 20-B-pillar's STL and dimensions.

The geometric modeling of the B-pillar mold was developed using Autodesk Maya, following similar procedure adopted in the previous case study: starting from the imported STL file, an initial extrusion was performed to assign thickness to the part, transforming the surface geometry into a solid volume. Subsequently, additional perimeter extrusion were added. These features serve to facilitate prepreg positioning, ensure effective vacuum sealing, and provide a clear trimming reference for post-curing operations.

Also in this case study, a key aspect of the design process was evaluating which side of the component would be used for lamination. As shown in *Figure 20*, the two sides of the B-pillar section have different geometries: one side is concave, while the other is convex.

Lamination was carried out on the concave side, using a female mold. This choice was driven by the need to achieve a high-quality surface finish on the internal side of the B-pillar - the one visible from the vehicle interior. Laminating into a concave geometry allows better conformation of the prepreg material to the mold, reduces the risk of defects such as wrinkles or voids, ensures a more uniform pressure distribution during vacuum bagging, and simplifies part demolding after curing.

Four demolding angles were designed and integrated into the geometry-identified as positions A, B, C, and D as show in *Figure 21*. These features are essential to facilitate the clean removal of the cured laminate from the mold without compromising the component's structural integrity.

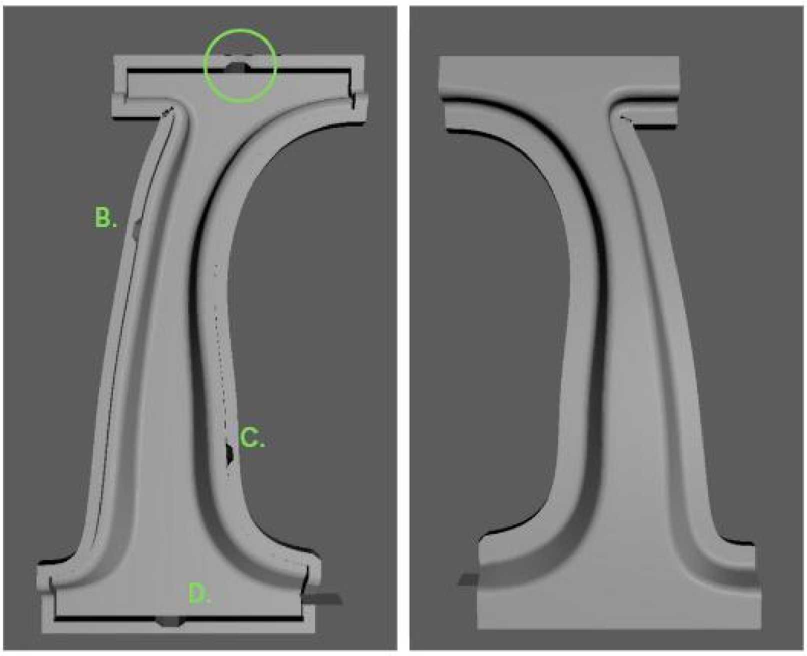

Figure 21- B-pillar mold highlighting demolding angles.

Due to the relatively large size of the B-pillar and the dimensional constraints of the available 3D printer's build platform, the mold was divided into two separate parts-labeled A and B. This design choice avoided the need to downscale the geometry, therewith preserving dimensional accuracy. The separation and joining features were modeled using Siemens NX, enabling precise alignment and the integration of a dual mechanical joining system.

Specifically, three bolt-and-nut fastening points were included to ensure structural stability during the lamination process, with through-holes designed at 6 mm in diameter to accommodate M6 screws. In addition, four dowel joints (spigot joints) were implemented to guarantee correct self-alignment of the two halves: cylindrical pins with a diameter of 5 mm were modeled on one component and fitted into matching holes on the corresponding side. The selected dimensions accounted for functional tolerances, allowing both ease of assembly and secure fitting. A detailed view of the interlocking dowel system is shown in *Figure 22*.

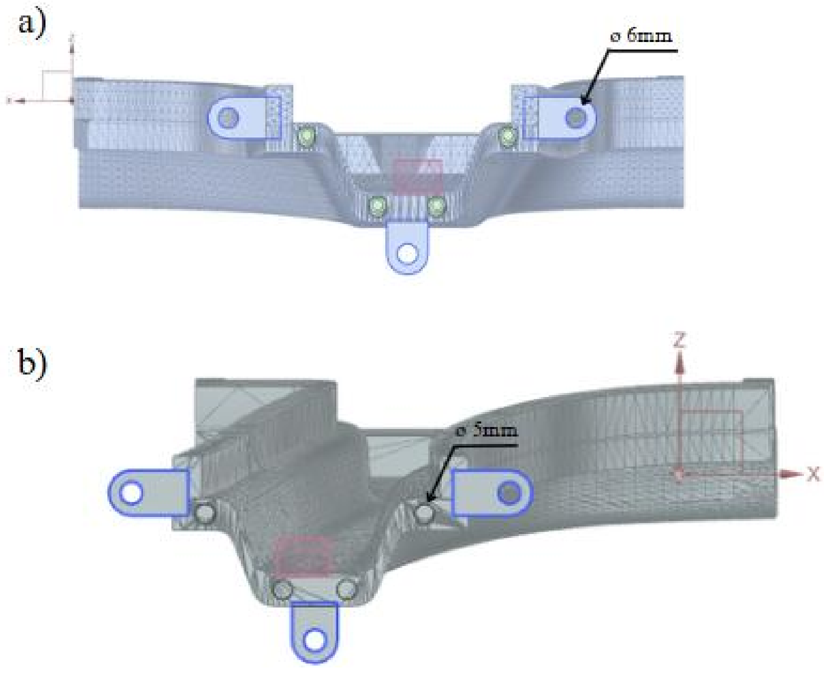

Figure 22- Exploded view of the mold in Siemens NX, showing the joining system:: (a) Part A, (b) Part B.

For this case study, no remeshing operations were required, as the initial STL file already provided a well-defined and structured mesh. Differently from the first case study, which involved the manual modeling of the mask and thus required specific interventions to improve mesh quality, this model was directly derived from an accurate digital acquisition.

The mold corresponding to the 2° case study, ready to print, is shown in *Figure 23*.

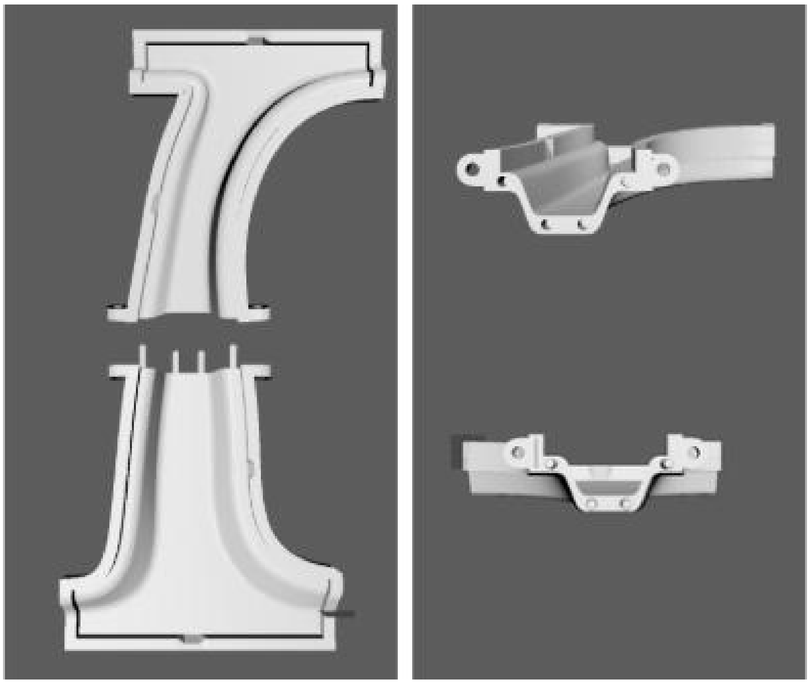

Figure 23- B-pillar final mold.

3.3. 3D printing process

Once the CAD modelling of the mold components for both case studies was completed, the process proceeded to the additive manufacturing phase using UV light photopolymerization technology. The hardware selection focused on resin-based 3D printers available in the laboratory and compatible with the previously selected Phrozen TR300 Ultra-High Temp Resin and Phrozen Ceramic Pro, Phrozen Sonic Mighty 4K. [24] This printer, shown in *Figure 24* utilize LCD technology to cure the resin layer by layer, with available building volume of L20 x W12.5 x H22 cm.

Figure 24- Phrozen Sonic Mighty 4K. [24]

To plan the printing process, the CHITUBOX Basic software [31] was employed. This tool allows for the simulation of the entire additive manufacturing workflow, from the import of STL files to the generation of machine-specific slicing code, tailored according to the selected printer and resin. A preliminary evaluation of the optimal print orientation (vertical or horizontal) was carried out, taking into account parameters such as the number and distribution of support structures, the contact area with the build plate, and the estimated print time.

Figures 25 shows the simulated print configurations with the softwere for both case studies. The simulations include visualizations of model orientation and generated supports, which were optimized to minimize contact on functional surfaces and ensure mechanical stability during the printing process. As previously mentioned, case study 2 was divided into two separate parts due to its overall volume; the two halves were printed at two different times as independent print jobs.

The main technical specifications of the 3D printer used for the fabrication of the molds are summarized in *Table 4*, includingresolution, printing speed, and light source. These characteristics define the machine's capability to produce accurate and detailed components suitable for composite processing.

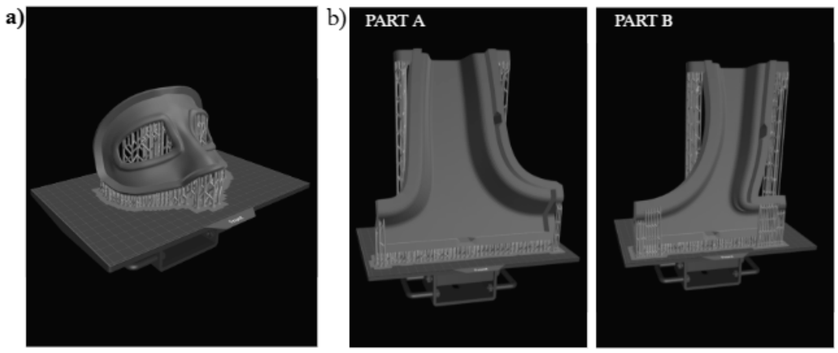

Figure 25- Print setup of the mold in Chitubox : a) Face Mask mold, Version B, b) the B-Pillar mold- Part A on the left and Part B on the right.

Figures 26 and *Figure 27* display the completed molds after support removal, highlighting the surface quality and geometric accuracy of the printed components.

Specifically, *Figure 26a* shows the first mold version, fabricated exclusively using a high-performance polymer resin. In contrast, the second version- characterized by thinner, non-perpendicular edges- was produced using two different materials: a polymer resin (*Figure26b)* and a ceramic-filled resin (*Figure 26c*). Both materials exhibit clean contours and well-defined features. Notably, the Ceramic Pro mold presents a smoother and more uniform surface finish, with fewer visible layer lines, an effect likely attributable to the higher resolution and enhanced surface properties of the ceramic-filled resin.

Figure 27 shows the B-pillar mold, divided into sections A and B, also post-processed and manufactured solely in polymer resin. Actual printing times for each model are reported in *Table 5*.

Figure 26- Fabricated Face Mask molds: (a) Version A printed in TR300 resin; (b) Version B printed in TR300 resin; (c) Version B printed in Ceramic Pro resin.

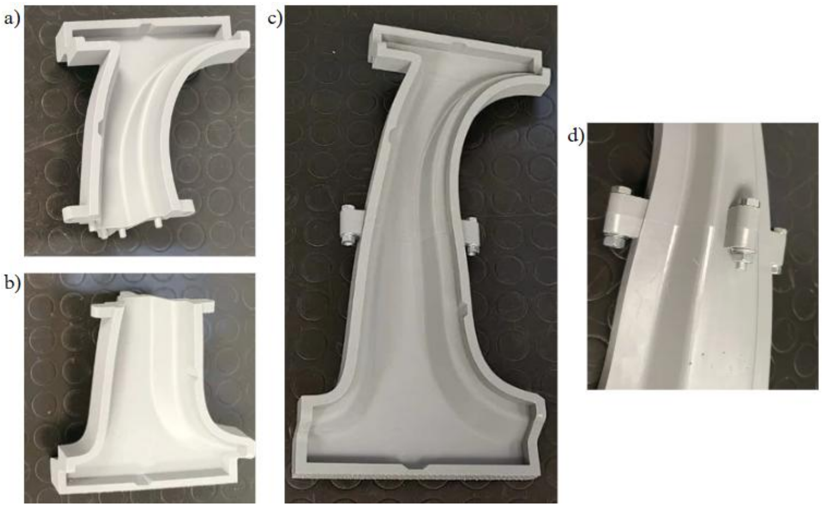

Figure 27- Fabricated B-Pillar mold: a) part B, b) part A, c) assembled component, d) focus on joints.

Table 4- Printer parameters.

PARAMETER	VALUE
Build Volume	200 x125 x 220 mm
XY Resolution	52 µm (4K, 3840 × 2400 pixels)
Light Source	405 nm ParaLED Matrix 2.0
Release Film	FEP Film
Expousure Time	2,20 s
Lift Distance	8,00 s
Lift Speed	60,0 s
Bottom Exposition	25,0 s
Layer Height	0,10 mm
Retfract Speed	150 mm/min

Table 5- Printing time required for the fabrication of the molds.

COMPONENT	TIME
Mask A- first CAD version- TR300 resin	~ 4 h 30 min
Mask B- second CAD version- TR300 resin	~ 4 h 10 min
Mask C- second CAD version- ceramic pro resin	~ 4 h 50 min
B-pillar- part A	~ 11h 6 min
B-pillar- part B	~ 9 h 26 min

Before proceeding with lamination, all 3D-printed components were subjected to a UV post-curing cycle to complete the photopolymerization and improve their mechanical and thermal stability. Components printed with TR300 resin underwent a 5-minute exposure, while those made with Ceramic Pro resin, due to their high ceramic content, required a 30-minute cycle. This treatment allows for full crosslinking of the resin matrix, increasing surface hardness and dimensional accuracy while reducing internal stresses. *Figure 28* shows the mask B placed inside the UV curing system during this process.

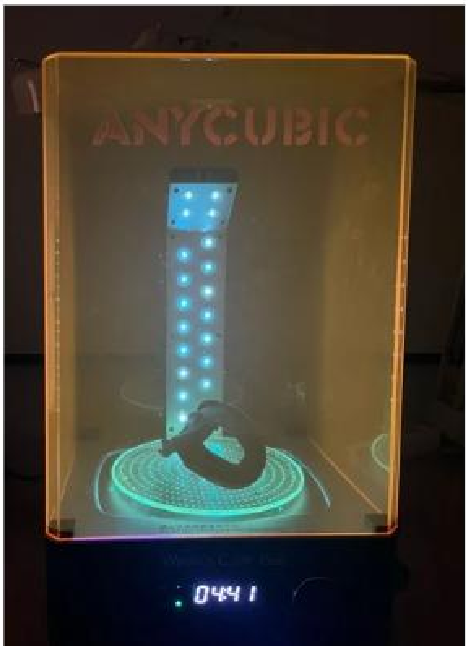

Figure 28- Face Mask mold- Version B TR300- placed inside the UV curing system during the post-curing process.

3.4. Unfolding process

Before proceeding with the lamination of composite material components, it is necessary to undertake a preliminary and fundamental phase: the generation of the unfolding of the lamination surface. This operation was performed using Blender software [32], leveraging its advanced UV Mapping functionalities. The goal of this phase is to project the curved surface of the mold model, defined in three-dimensional space (*Figure 29*), onto a two-dimensional plane, enabling an accurate and practical representation of the area to be covered with prepreg layers.

This unfolding is not a mere geometric transposition; rather, it serves as a crucial tool for planning the lamination process. It allows for the early identification of critical regions of the component, characterized by high curvature or geometrical complexity, and supports the prediction of unavoidable distortions that occur when flattening a curved surface. From a mathematical standpoint, it is impossible to develop a non-developable curved surface onto a plane without introducing deformation. These distortions may manifest as local stretching, compression, or shearing, and must be carefully analyzed and mitigated, as they directly influence cutting accuracy and the proper adhesion of the prepreg material to the mold.

To reduce these effects, it is essential during the unfolding process to introduce cuts along the developed surface. These cuts serve a dual purpose: on one hand, they allow for the redistribution and containment of geometric distortions by channeling them toward less critical areas; on the other hand, they segment the prepreg into more manageable patches, thereby improving the material's conformability.

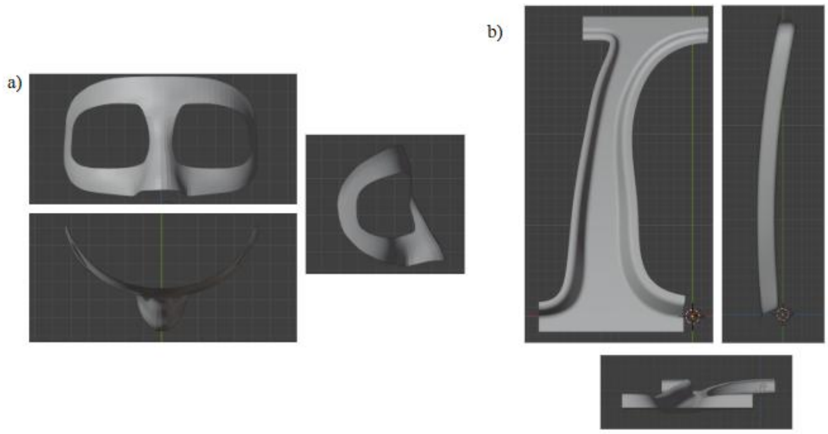

Figure 29- Lamination surface views of the molds: (A) Face Mask and (B) B-Pillar.

This design phase results in a set of cutting patterns that guide the trimming of each prepreg layer. During the lamination process, each layer is cut according to a specific pattern derived from the unfolding, but the cuts are deliberately staggered between layers. This strategy helps to avoid the overlap of discontinuities, thereby reducing the risk of stress accumulation, localized weakening, and the onset of delamination.

The visual analysis of the unfolding also enabled the simulation of cut placement across different laminate layers. *Figure 30* shows three alternative unfolding configurations developed for Case Study 1, each characterized by a distinct cut placement strategy aimed at optimizing the balance between structural performance, aesthetic quality, and manufacturing feasibility. In particular, the nose area of the component was identified as the most critical region due to the coexistence of negative and positive curvatures, which complicate the continuous laying of prepreg. For this reason, in all configurations, cut placement was carefully concentrated near this area to maximize conformability, minimize distortion, and ensure the aesthetic and functional continuity of the final laminate.

In contrast, only two unfolding configurations were developed for Case Study 2 (*Figure 31*), as the geometry of the B-pillar features smoother and less critical curvature transitions. These less severe geometric variations reduced the need for complex cut planning.

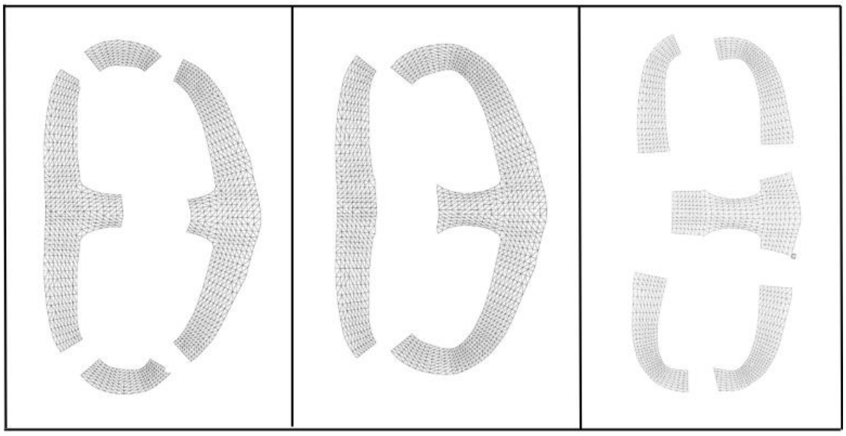

Figure 30- Unfolded lamination surface of the Face Mask mold with indicated cutting lines.

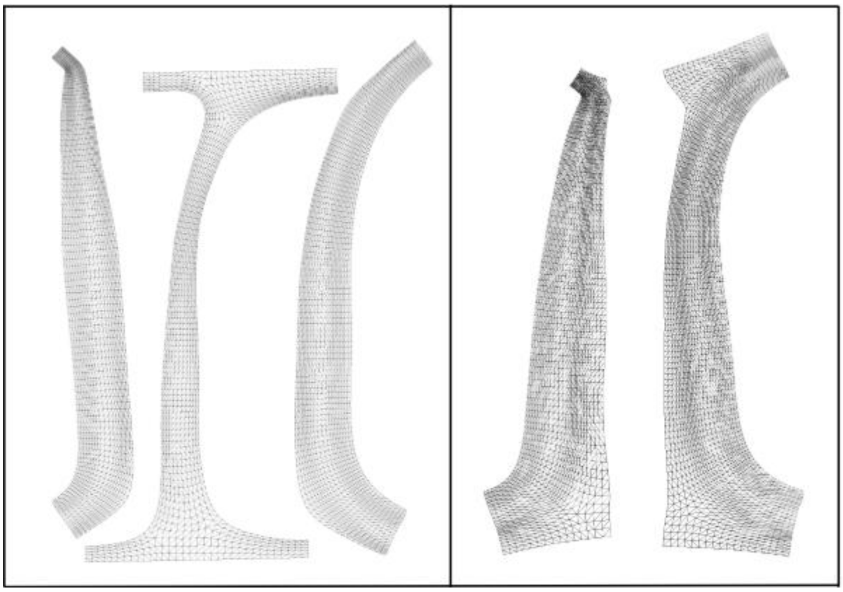

Figure 31- Unfolded lamination surface of B-PIllar mold with indicated cutting lines.

3.5. Lamination process

Lamination represents one of the most delicate stages in the manufacturing process of composite components, as it directly affects the mechanical properties and overall integrity of the final product. In particular, when performed manually, it requires close control, operational expertise, and a deep understanding of the prepreg behavior during each phase of the process. For this reason, the entire cycle was supervised by experienced laboratory technicians.

The material used was the unidirectional (UD) Toray T700S prepreg, already introduced in the chapter dedicated to material selection. Supplied in rolls protected by films on both sides, the prepreg was stored at low temperatures to preserve its properties. After extracting the amount required for the process, the remaining roll was immediately returned to refrigerated storage, thus avoiding any prolonged exposure to ambient temperature that could compromise the stability of the resin matrix.

The preliminary phases of lamination involved several steps. First, the treatment of the mold surfaces with a release agent: the product was applied manually with a bruch in four successive layers, allowing each coat to dry before applying the next. This treatment, lasting approximately 20 minutes per mold, was essential to facilitate the removal of the finished component and to prevent surface damage during demolding.

Subsequently, the cutting of the ply patterns was carried out: the templates obtained from the CAD unfolding phase were manually transferred onto the prepreg and trimmed accordingly (Figure 32). As much as possible, cutting was performed along the fiber direction of the unidirectional prepreg, ensuring better mechanical strength and reducing fraying at the edges, resulting in cleaner and more manageable ply patterns.

Perpendicular cuts- generally more difficult to execute due to the stiffness of the fibers- were limited to the minimum necessary.

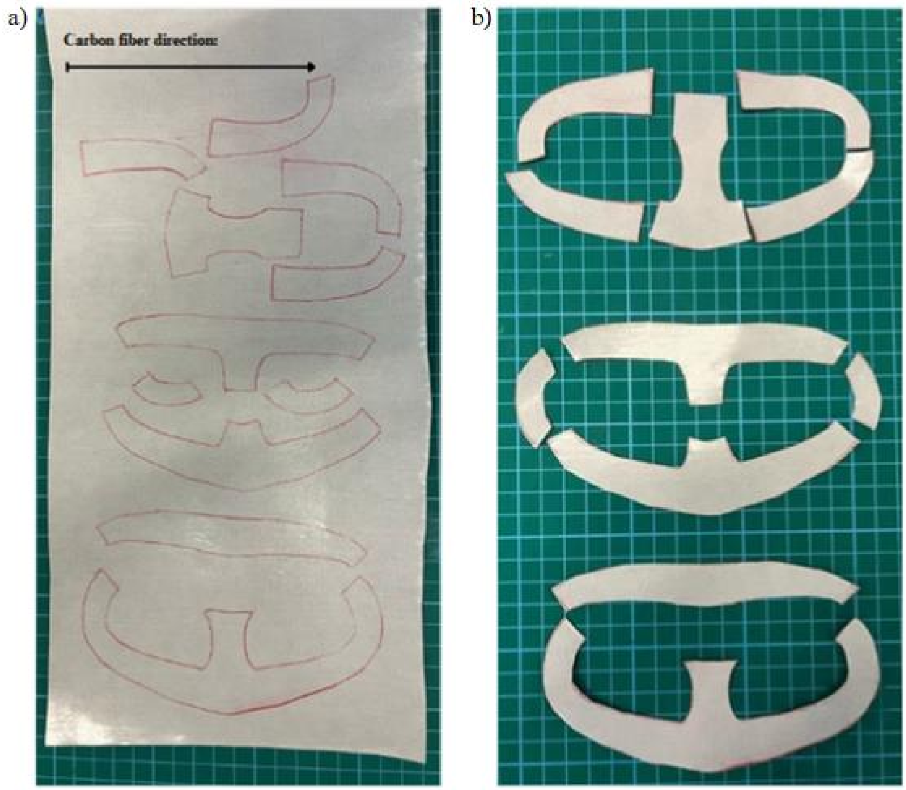

Figure 32- (a) Drawing of the ply patterns to be cut from the prepreg sheet; (b) corresponding cut pieces ready for lay-up.

The cut pieces were then subjected to dimensional verification, as shown in *Figure 33*, while still protected by the polymer films. After any necessary adjustments, the protective films were carefully removed using precise movements. It was essential to act perpendicularly to the fiber direction, in order to avoid fraying or breakage.

Figure 33- Dimensional verification of the cut prepreg pieces while still covered by protective polymer films.

Lamination was then performed by placing the first layer on the treated surface, followed by the subsequent layers, with special care paid to correct fiber orientation and uniform placement. This phase highlighted the typical challenges of working with unidirectional prepreg: due to the nature of the material, the geometry of the cut can become unstable, with fibers tending to lift, fold, or lose continuity during handling. Particular attention was given to high-curvature areas and sharp corners, where the risk of defects such as air bubbles, wrinkles, or local distortions is increased.

The result for Case Study 1, Version A is shown in *Figure 34*. In this configuration, three layers of material were applied. However, due to the reduced thickness of the component, difficulties were encountered during demolding.

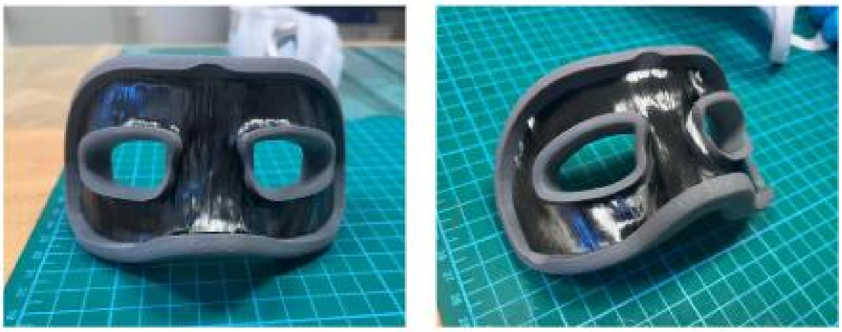

Figure 34- Face Mask Mold- Version A- after completion of the lamination, with all prepreg layers applied.

For this reason, in the versione 2 of the mask (*Figure 35*) and the B-pillar (*Figure 36*), a higher number of layers was chosen - respectively 7 and 6 - in order to improve structural stiffness and facilitate part removal from the mold without damaging the component.

An additional complexity arose from the thermal behavior of the prepreg: even brief exposure to room temperature caused a gradual softening of the resin matrix, leading to swelling and difficulties during placement. To mitigate such effects, it is important to acknowledge the industrial best practice of working in climate-controlled environments and applying vacuum after each layer, to improve compaction and reduce internal defects. This procedure, although not implemented due to logistical and equipment constraints, remains a significant point of reference for future development of the process in professional contexts.

Figure 35- Face Mask Mold- Version B - after completion of the lamination, with all prepreg layers applied.

Figure 36- B.pillar Mold after completion of the lamination, with all prepreg layers applied.

After completing the lamination, the setup of the vacuum bag system (*Figure 37*) was carried out in preparation for the autoclave curing stage. This step also required particular attention, as even the smallest air leak could compromise vacuum stability and, consequently, the quality of the final laminate.

Preparation began with the cutting of the vacuum bag film, a flexible, heat-resistant, and airtight plastic film, sized to ensure a generous margin around the part. It is crucial that the bag is not excessively tight: during suction, the film is drawn inward, and if there is insufficient slack, it could tear or hinder uniform pressure distribution.
Next, the sealant tape- a plastic butyl-based, self-adhesive, and moldable tape also resistant to high temperatures- was applied along the edges of the mold, allowing a partial closure of

the bag while leaving an opening to complete the internal setup. At this point, the laminated component, covered with a layer of peel ply a porous release fabric in direct contact with the prepreg. This layer prevents bonding with the auxiliary materials and enables the evacuation of air and volatiles through the surface of the laminate. Over the peel ply, a thermal breather blanket was placed, extending continuously up to the area where the vacuum valve would be installed. This layer performs a dual function: it ensures uniform heat distribution during curing and creates a continuous path for air and volatiles toward the vacuum outlet, supporting efficient pressure equalization.

Subsequently, the vacuum valve was installed at the designated outlet point, ensuring good contact with the breather blanket to allow effective suction.

After verifying the correct positioning of all auxiliary elements, the final sealing of the bag was completed along the remaining perimeter, making sure the contact interface with the sealant tape was continuous and free of leaks.

Finally, a leak test was carried out to verify vacuum stability: the absence of pressure drops or air infiltration confirmed the correct setup of the system, making it ready for the start of the autoclave curing cycle. *(Figure 38*)

Figure 37- Vacuum setup

Figure 38- Vacuum system functionality check.

3.6. Curing Cycle in Autoclave

Once the vacuum integrity has been verified, the system is transferred into the autoclave (*Figure 39*). During positioning, the vacuum bag is connected to the external pump, which remains active throughout the entire curing cycle, maintaining a stable level of vacuum inside the system. This setup is essential to facilitate the evacuation of any residual air trapped within the laminate, thereby preventing porosity formation and ensuring proper compaction between layers.

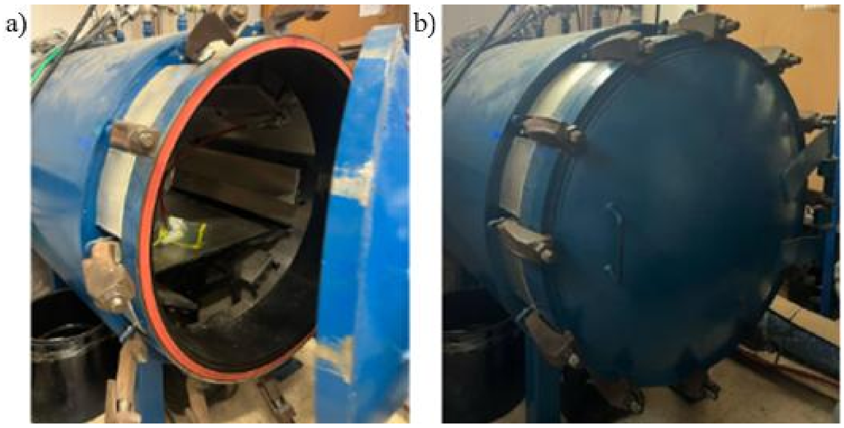

Figure 39- a) Autoclave open with the vacuum system setup inside; b) Autoclave closed, ready for the curing cycle.

After securely closing the pressurized oven, the thermopressure cycle is initiated, as shown in *Figure 40*. The cycle lasts about 3 hours and includes:

— *Heating*: Ramp from 25 °C to 120 °C in 50 minutes (~2 °C/min), with no applied pressure.

— *Pressurization and hold*: Pressure is increased to 5 bar over 10 minutes, followed by a 70-minute hold at 120 °C and 5 bar to ensure proper resin consolidation and curing.

— *Cooling*: Controlled cooling from 120 °C to room temperature (~2 °C/min), after gradual depressurization.

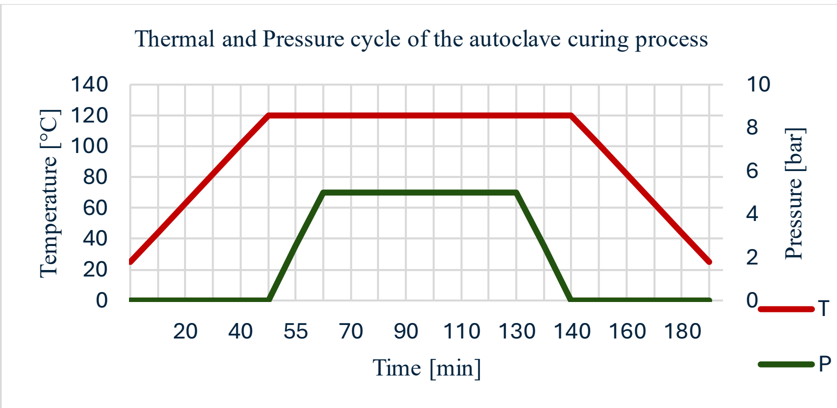

Figure 40- Thermal and Pressure Cycle of the Autoclave Curing Process

The temperature achieved during the cycle enables the complete chemical crosslinking of the epoxy matrix, through the formation of covalent bonds between polymer chains. This process results in the transition of the material from the B-stage (partially crosslinked) to its final solid state, ensuring dimensional stability and the required mechanical properties of the composite.

At the end of the curing cycle, the components are removed from the oven and released from the vacuum system. *Figures 41*, *Figure 42* and *Figure 43* show the components inside the mold and after demolding.

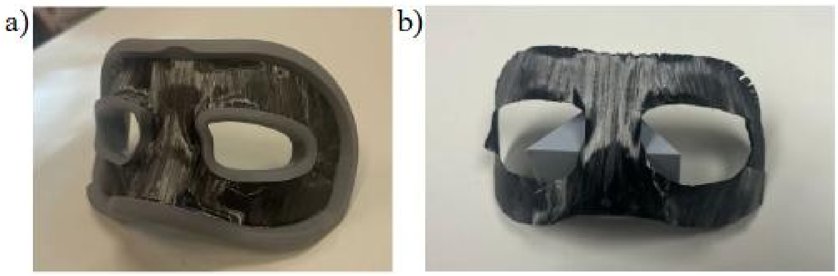

Figure 41- Face mask – version A (TR300 resin):(a) Component inside the mold, (b) Component after demolding.

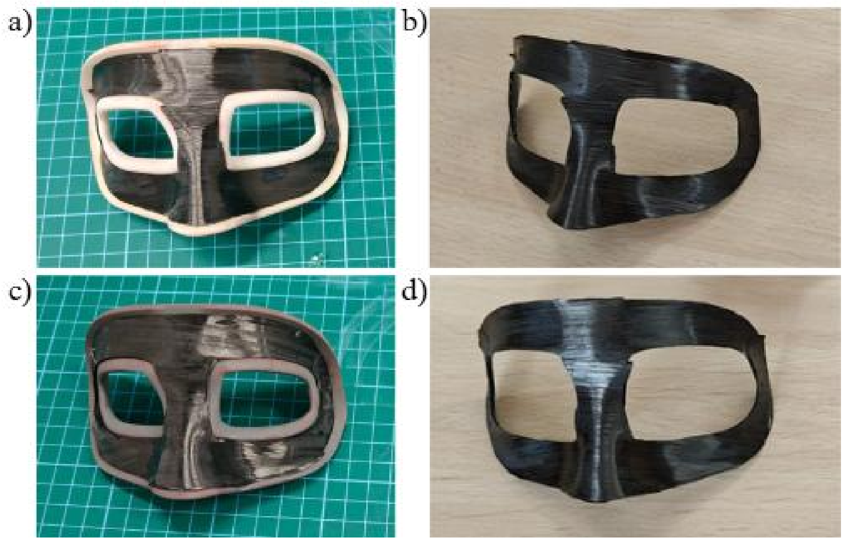

Figure 42- Facial orthosis mask – version B: (a) Component inside the mold – TR300 resin, (b) Component after demolding – TR300 resin, (c) Component inside the mold – Pro Ceramic resin, (d) Component after demolding – Pro Ceramic resin.

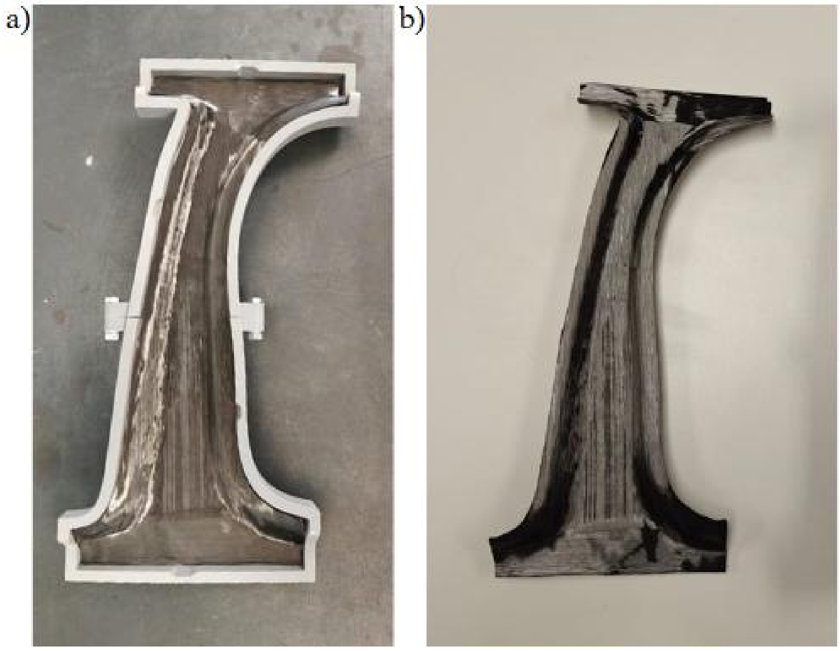

Figure 43- B-pillar (TR300 resin):(a) Component inside the mold, (b) Component after demolding.

4. Result and discussion

This chapter summarizes and critically discusses the experimental results obtained from the two selected case studies, with the aim of validating the use of 3D printing based on Digital Light Processing (DLP) technology for the production of molds intended for the manual lay-up of carbon fiber prepreg and subsequent autoclave curing.

The evaluation focuses primarily on the performance and behavior of the molds throughout the entire process, and is limited to a visual analysis of the produced laminates. No mechanical testing or in-depth investigations into the performance properties of the laminates were carried out, as such aspects fall outside the scope of the objectives defined for this research, which aims to assess the technical and economic feasibility of additive manufacturing applied to mold production.

4.1. Case study 1: Face Mask

In this specific case, it is possible to make observations regarding both the geometry of the molds and the materials used. The two developed versions made it possible to experimentally assess the importance of CAD design: the optimization implemented in version A of the mold- featuring thinner and outward-sloping perimeter edges- facilitated component demolding, positively affecting not only the quality of the laminate (which exhibited fewer delaminations and reduced risk of fracture), but also minimizing the risk of damage to the molding surface or to the mold itself.

As for the materials used to print the molds, both TR300 and Ceramic Pro Resin proved adequate in terms of resistance to the thermopressure cycle in the autoclave. As shown in *Figure 44* and *Figure 45*, no deformation, cracking, or dimensional instability was observed. Surface alterations were limited to release agent residues, which were easily removed through manual cleaning operations, confirming the potential for mold reuse across multiple cycles.

However, operational differences between the employed materials did emerge. The ceramic resin exhibited greater intrinsic brittleness, making it more susceptible to accidental damage during post-processing and handling phases, although this did not compromise its integrity during autoclave curing. In contrast, TR300 resin, due to its greater ductility, proved to be more suitable for less controlled environments or those involving frequent handling.

Figure 44- Face Mask mol- version A- after curing cycle in Autoclave

Figure 45-Face Mask mold- version B- after curing cycle in Autoclave. a) TR300, b) Pro Ceramic.

From an economic perspective, 3D printing allows for a significant cost reduction compared to traditional methods. The production of a TR300 mold weighing approximately

60 g entails a material cost of around €5, to which approximately €200 for CAD modeling (estimated at 5 hours) and €150 for printing and post-curing operations must be added, for a total of around €350. In the case of the Ceramic Pro Resin, the material cost rises to around €20, bringing the total to approximately €400. For comparison, according to Mendoza et al. (2020) [17], the production of an aluminum mold for personalized biomedical applications requires 20–30 hours of machining and total costs exceeding €1500, justified by a durability of over 30,000 cycles. However, for small-scale production runs, such as the orthotic mask analyzed in this study, additive manufacturing proves to be an order of magnitude more cost-effective. A summary of the comparison data is provided in Table 6.

Table 6- Comparative analysis of different mold manufacturing methods.

MANUFACTURING METHOD – MATERIAL USED	MANUFACTURING TIME (h)	COST (€)	MOLDING CYCLES
CNC MACHINING – ALUMINUM	*~20-30*	*~1500*	>30000
3D-PRINTED – TR300 RESIN	*~10*	*~350*	<5
3D-PRINTED – CERAMIC PRO RESIN	*~10-15*	*~400*	<5

In summary, the first case study confirmed the technical and economic feasibility of 3D printing for the fabrication of reusable molds in the field of personalized biomedical applications, while also highlighting the importance of process-oriented design and careful material selection. Although the molds were subjected to only one autoclave curing cycle, the absence of damage suggests the possibility of reuse for a limited number of cycles (fewer than five), in line with the one-off nature of the produced device. In applications such as the one analyzed here- the production of a custom facial orthotic mask- extensive use of the mold is not expected, since each component is designed for an individual patient. Moreover, although no mechanical testing was performed on the laminates- since it falls outside the scope of this thesis- the visual and functional evaluation of the obtained results proved sufficient to draw meaningful conclusions regarding the effectiveness of the adopted approach.

4.2. Case study 2: B-Pillar

In the second case study, since no geometric variants or alternative materials were developed, the analysis focused on the behavior of the specific mold produced. The material used demonstrated good resistance to the planned curing cycle, enabling the fabrication of a technically valid component. However, as shown in *Figure 46*, a comparison between the mold pre- and post-curing reveals localized deformations near the joint between the two mold halves.

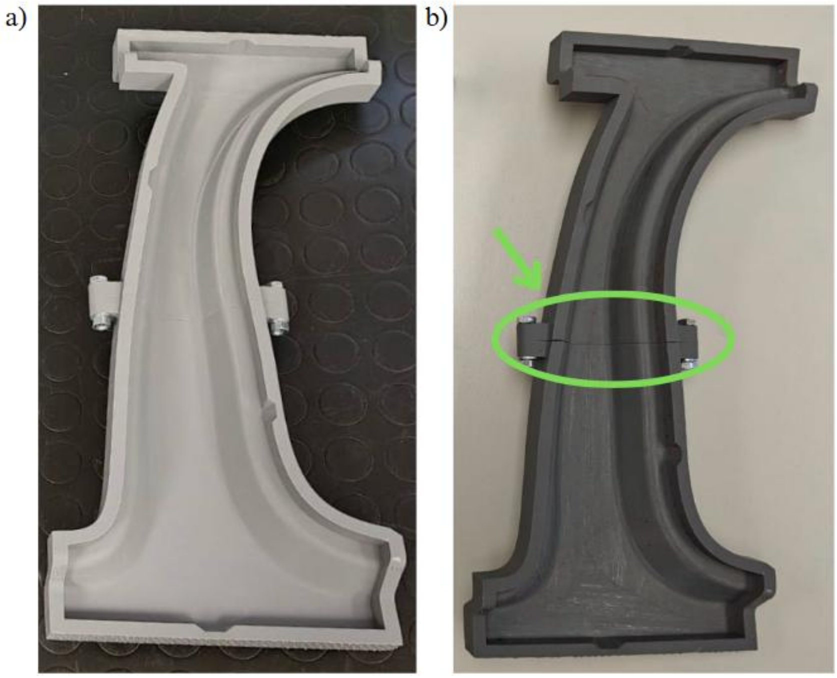

Figure 46- B-pillar Mold: a) before process, b) after autoclave curing.

Although both parts were made from the same material-and therefore share the same coefficient of thermal expansion (CTE)-they exhibited uneven residual stress release. These effects, amplified by the rigidity of the constraints and the structural joint, compromised the proper mating of the contact surfaces, making the mold unsuitable for reuse in subsequent curing cycles.

This behavior aligns with observations by Kamaruddin et al. [33], who highlighted the influence of geometry and fixturing on the development of residual thermal stresses. Within this context, a possible mitigation strategy is proposed, based on partially or fully opening the mold during the cooling phase at an intermediate temperature (70–80 °C), when polymerization is complete but residual stresses have not yet been fully released.

Although Wang et al. [34] do not directly address joint issues, their study confirms that demolding temperature significantly affects final laminate deformation, suggesting that controlled management of this phase could help reduce distortion phenomena.

In conclusion, the second case study demonstrated the effectiveness of the chosen material for single lamination cycles, but also highlighted the limitations of the adopted geometric design. The deformations occurring at the joint prevent repeated use of the mold, excluding its application in serial production contexts.

5. Future Perspettive and Challenge

Despite the encouraging results obtained in this study, several open issues remain to be addressed in order to fully exploit the potential of additive manufacturing (AM) for producing molds used in composite lamination processes.

First and foremost, process repeatability and production scalability are fundamental aspects that require further investigation. This work demonstrated that AM is a valid solution for low-volume, customized production typical of personalized medical devices such as orthotic masks; however, scaling up to larger production batches or more complex geometries will likely require more detailed study and optimization of printing technologies. A significant limitation is the current build volume of 3D printers, which necessitates splitting the mold into multiple parts for assembly. Although practical, this approach introduces new challenges, particularly concerning precise alignment of joints, sealing during autoclave cycles, and overall structural robustness.

Another critical point concerns the long-term stability of the molds, especially when subjected to multiple curing cycles. In our case, the molds showed stability after a single cycle, but for broader industrial or medical use, a thorough investigation of their thermal and mechanical resistance over time is necessary.

It is also worth highlighting that additive manufacturing offers significant advantages during the prototyping phase: the ability to rapidly produce scaled models or prototypes enables testing and refining mold geometry, assessing tool functionality, and identifying manufacturing issues early on, thus saving time and costs in subsequent large-scale production. This is particularly valuable when working with highly customized components and complex geometries.

Finally, the development of in-situ monitoring systems and advanced quality control methodologies during printing and post-processing could greatly enhance the reliability of AM-produced molds, facilitating their adoption in both industrial and biomedical sectors.

In summary, the most promising future research directions include:

— deepening the understanding of mold behavior under multiple curing cycles, especially for structural applications where strength and durability are crucial;

— addressing the issue of residual stress release, with particular attention to modular joints, to prevent deformations that compromise mold functionality;

— developing design and process solutions to overcome the size limitations imposed by current printing technology, while ensuring precision, sealing, and mechanical integrity during autoclave cycles.

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