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Processing of sheets made of long fibers reinforced plastics by SPIF

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Abstract. The flexibility of the Single Point Incremental Forming (SPIF) has been exploited in processing of sheets made by fiber reinforced polymers. Indeed, polymer-based sheets are always more employed in product planning, meeting the increasing demand of lightweight structures. However, considering the SPIF features, especially the need to totally clamp the formed sheet along its edges, processing of long-fiber reinforced sheets is critical owing to the brittleness of the fibers, whose length must be preserved. The SPIF dynamics of a customized process solution to be used for long fibers reinforced thermoplastics (LFRTPs) were already proposed and analyzed by FE simulations. Herein, the design of the equipment that allows the process to be executed was proposed detailing it in each part. In particular, the idea was based on assembling a working room that was designed to be able to control both: a) the desired process temperature maintaining it constant during the whole forming step looking at the glass and melting point of the polymeric matrix; b) a hydrostatic pressure on the bottom side of the sheet to guarantee its proper shaping. Moreover, numerical simulations were also executed to locally analyze the forming behavior of the sheet at changing of some specific properties.

Introduction

In the pursuit of lightweight design, high-strength materials, long fiber composites have emerged as a promising candidate for various engineering applications. These materials, characterized by the incorporation of continuous fibers within a polymer matrix, offer exceptional mechanical properties and design flexibility. Specifically, long fiber composites, characterized by extended and continuous fibers embedded within a polymer matrix, exhibit remarkable strength, stiffness, and fatigue resistance compared to traditional materials. However, the manufacturing of long fiber reinforced thermoplastic sheets (LFRTPs) presents a myriad of challenges that necessitate careful examination to fully unlock the potential of these advanced materials. The integration of long fiber composites in various industries has been a revolutionary stride towards achieving lightweight structures with enhanced mechanical properties. Long fiber composites have found applications in industries ranging from automotive to aerospace, where the demand for lightweight yet durable components is paramount. The intrinsic advantages of LFRTPs, such as enhanced tensile strength and impact resistance, position them as a preferred choice for structural elements. Despite these advantages, challenges arise during the manufacturing processes due to the inherent anisotropic nature of the material. Conventional manufacturing technologies, such as injection molding and compression molding, struggle to seamlessly shape LFRTPs without compromising their mechanical properties. In this perspective, as with any cutting-edge technology, the implementation of long fiber composites is not without any challenges. Several technologies are commonly used for shaping long fiber thermoplastic composites, as summarized in Table 1 [1,2].

Table 1 - Manufacturing process adopted for long fiber composites

Process	Description	Weakness
Injection molding	Molten thermoplastic material is injected into a mold cavity, where it solidifies into the desired shape	Tooling costs can be high, and it may be challenging to achieve uniform fiber orientation in complex parts
Thermoforming	This process involves heating a pre-consolidated thermoplastic sheet until it becomes pliable, and then forming it into a specific shape using a mold	Limited to simple shapes, may not be suitable for high-strength applications
Pultrusion	Continuous process where fibers (usually glass or carbon) are impregnated with a thermoplastic resin and pulled through a heated die to shape the composite	Limited to linear shapes, may not be suitable for complex three-dimensional parts
Stamping	Composite sheet are presses between dies	Limited to specific and simple shapes and may have higher tooling costs

In recent years, the field of materials science and manufacturing has witnessed a paradigm shift with the advent of Single Point Incremental Forming (SPIF). This innovative manufacturing technique has garnered substantial attention for its potential to revolutionize the production processes [3], particularly in the domain of unconventional materials [4,5]. This paper explores the innovation prosecutable by the intersection of SPIF and long fiber thermoplastics use, aiming to shed light on the synergies that can propel advancements in both application fields. In contrast with the conventional manufacturing techniques, SPIF stands out as a promising alternative, offering a more agile and cost-effective approach to shaping intricate geometries with reduced material waste. By exploring the synergy between this innovative forming technique and long fiber composites materials, we aim to uncover novel pathways for enhancing manufacturing efficiency, material properties, and ultimately fostering a new era of design possibilities.

The designed Equipment

An equipment was designed pointing out each component required to perform the forming phase of SPIF on sheets made by LFRTPs. A scheme of the whole experimental equipment is reported in Fig. 1.

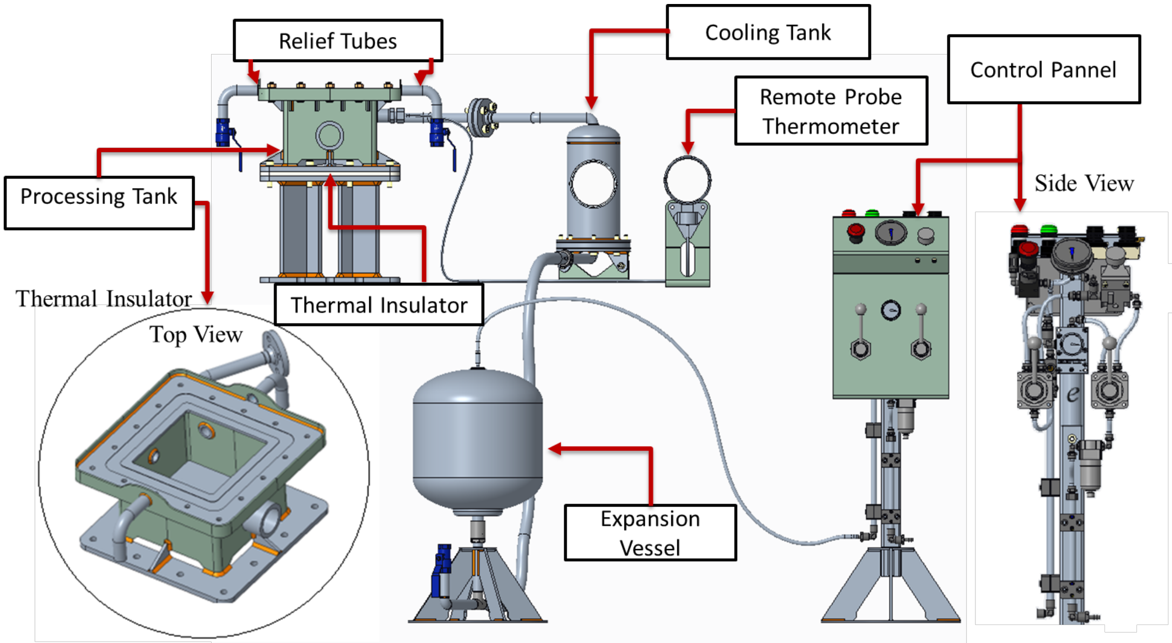

Fig. 1 – Scheme of the designed equipment

Specifically, the equipment was conceived with the aim to be able to control working temperature and back hydrostatic pressure, continuously, in the working phase. The SPIF of LFRTPs is executed by using a metallic sheet in between the rigid tool and the composite sheet to be processed [4,5]. Both the metal and the composite blanks have to be totally blocked along their perimeter on the upper part of the processing tank covering and sealing, as a lid, the working area.

It has to be highlighted that the long fibers, both carbon and glass fibers, that are commonly used to reinforce polymeric matrices, can not be blocked being characterized by really high breakability and absolutely no plastic deformation. Taking that into account, the idea was to divide the polymer-based blank in two portions leaving the external frame, used for its clamping, without reinforcements (Fig. 2).

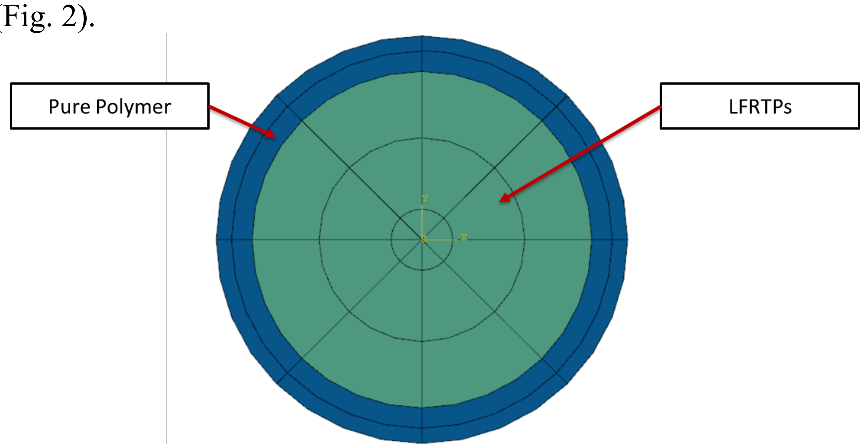

Fig. 2 – A sketch of the working composite sheet

By doing so, the composite sheet, at the working temperature, chosen taking into account the glass and melting temperature of the processed thermoplastic matrix and depending on its level of crystallinity, is sagging affecting the dimensional accuracy in the forming phase. For that reason, the composite sheet has to adhere to the metallic blank up to both forming and cooling phases are completed.

For that reason, a specific fluid, for example a thermal oil, is pressurized inside the processing tank resulting in a hydrostatic force that pushes the composite sheet to the metallic one. This pressurized fluid allows the contact between the two sheets to be obtained, exactly. In detail, before the SPIF starts, the processing tank is filled up to the clamping plane by this oil. Two relief tubes are utilized to ensure the complete filling of the working volume avoiding air pockets under the sheets.

The pressurized fluid is further utilized to control the working temperature of the plastic material avoiding thermal fluctuation that can affect the formability of the sheet. An electrical resistance is inserted in the oil, in the processing tank's volume, to heat the system and control the temperature, remotely, by a thermometric probe. Furthermore, the processing tank is isolated by the basis of the equipment by placing on its bottom a thick plate of ceramic material acting as thermal insulator (Fig.3).

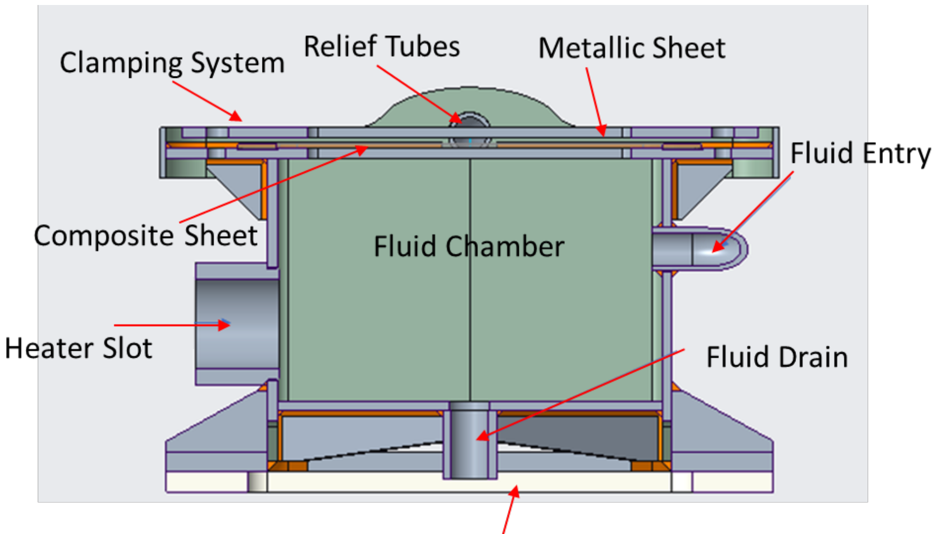

Fig. 3 – A section of the designed processing tank

Summing up, the fluid inside the processing is employed for controlling both pressure and temperature during the SPIF's steps. The process monitoring has to take into account that, while the forming phase proceeds, the formed sheets go in the chamber of the processing tank reducing the volume taken by the oil. For that reason, in order to be able to make independent the hydrostatic pressure history from the rigid tool's position, an expansion vessel was introduced in the equipment working as an outlet for the fluid. The pressure in the working zone is, therefore, controlled, by setting with a control panel the desired pressure trend inside the expansion vessel.

For this purpose, a pneumatic regulator is employed with the aim to take an inlet air pressure, adjusting it automatically to follow the desired output pressure, namely the working pressure, and guaranteeing a stable functioning of the system by also using a vent valve.

A stratified thermal separator was, finally, placed at the exit of the processing tank, with the aim of reducing the temperature of the fluid before it reaches the expansion vessel. For safety reasons, indeed, the temperature of the pressurized oil has to be reduced before reaching the expansion vessel. This control was provided by monitoring the temperature by an additional thermometer placed in the thermal separator.

Finally, the control panel allows pressure and temperature to be regulated by the highlighted equipment relating these variables to the SPIF's specific phases.

Designed process solution investigated by FEM

Numerical simulations were set to investigate the mechanical behavior of the LFRTs sheets processed by SPIF using the highlighted process peculiarities. The aim is to gain through the numerical study a deeper understanding of the sheet deformation allowing the equipment construction to be validated. A single-point incremental forming (SPIF) process was proposed on LFRTPs blank consisting of a thermoplastic polypropylene (PP) matrix and a long glass fiber (GF) reinforcement. Specifically, the $[0/45/-45/90]_s$ or quasi-isotropic configuration was analyzed. In the simulation process, the possibility of applying the single-point incremental forming process (SPIF) assisted by a pressurized fluid was evaluated. The pressurized fluid could creep between the aluminum blank, which acts as a membrane, interposed between the composite blank and the tool, used in the incremental forming process. In order to avoid this problem, the implementation of a polymeric frame, of the same material as the matrix (PP), properly realized around the composite laminate (GFRP), has been proposed, which has the function of guaranteeing an optimal seal between the rigid support and the laminate and thus avoiding fluid leakage.

The FE numerical model was created by modeling four bodies: the deformation tool, the rigid support, the aluminum blank and the composite laminate blank, the latter made of GFRP and an external PP frame. A diagram of the assembly used in the simulation is shown in Fig. 4.

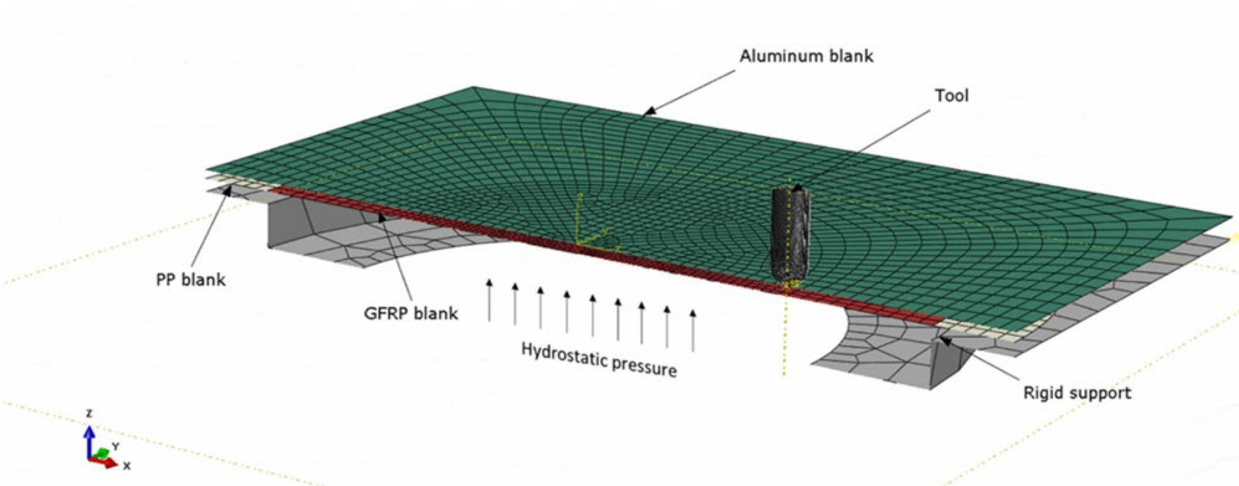

Fig. 4 - Cross-section view of the FE model assembly

The FE model was developed from a specific material model to be implemented for the definition of the virtual composite sheet. This sheet is made of GFRP and a part entirely of PP. In addition, PP, whose forming temperature is approximately 220 °C, was chosen as the matrix, considering its hygroscopic characteristics to carry out future experimental validation tests using the proposed process technology (Fig.1). Long glass fibers, not stitched into the pre-impregnated foils, are the reinforcement type. The volume fraction of fibers in each lamina is 60%. The virtual composite sheet was built considering an overlapping of laminas, under quasi-isotropic conditions, as described in Table 2. The mechanical properties of the lamina at working temperature are given in Table 3.

Table 2 - Configuration of GFRP panel

Laminate sequence	Diameter (mm)	Lamina Thickness (mm)	Laminate Thickness (mm)
$[0/45/-45/0]_s$	160	0.25	2

The mechanical properties of the lamina at working temperature are given in Table 2.

Table 3 - Mechanical properties of the utilized prepreg [6]

Parameters 220°C	E11	E22	μ12	G12	G23
Value	2.5 GPa	0.5 MPa	0.35	0.2 MPa	0.2 MPa

The laminas are set by taking into account their linear elastic properties and implementing Hashin's damage model [7] to study matrix and fiber failures. The parameters of the sheet constitutive model were set according to [5]. The dummy sheet used as a cover is a 2 mm thick aluminum alloy (AA-6056). The plastic behavior of sheet AA-6056 was modeled according to [5].

Numerical model

The finite element model of the proposed SPIF process was run with the FE Abaqus/CAE commercial code. Fig. 4 shows the cross-section of the FE model assembly based on the previously described process strategy. In detail, the rotational molding tool, modeled as a rigid body, is in contact with a square aluminum blank characterized by a 200 mm side and fixed in the periphery on a steel frame, modeled as a rigid body. A Coulomb friction coefficient of 0.1 between the tool and the metal plate was set [8, 5]. The outer edge of the panel is made of PP, which is melted under the chosen process conditions, while the remaining part is made of GFRP and is subjected to hydrostatic pressure simulating the presence of pressurized fluid. A constant pressure is set under the GFRP and PP sheet, as shown in Fig. 4. A friction-free approach was used between the two slabs, which were modeled as deformable bodies using shell elements (S4R). Simpson's integration rule with 5 integration points was modeled along the thickness direction, and approximately 3000 elements for the aluminum blank and 3500 elements for the GFRP and PP sheet were used. An explicit solver, with time and mass scaling, was used to accelerate the simulation. In particular, semi-automatic mass scaling with a target time increment of 2e-6 s was implemented. The tool path was defined by three tabular amplitudes and the total simulation time was set equal to 6 s.

Investigated process variables

A truncated cone was numerically formed. The cone is characterized by an inclination angle of 30°, a final height of 25 mm, and a base diameter of 100 mm. The effects on the quality of the formed parts, focusing on the surface quality, shape accuracy and/or local thinning of the sheet formed from GFRP and PP, were assessed by changing the pressure value on the back face of the GFRP and PP panel. Constant values of 0.01, 0.05, 0.1 and 0.2 MPa were assessed during the entire forming phase.

FE model results

This section focuses on the analysis of the numerical results obtained from the simulations carried out on the SPIF process. Specifically, the results of the model were evaluated both in the section realized in GFRP and in the frame realized in PP. The results were evaluated in terms of formability, thickness distribution and accuracy of the shape as the pressure exerted by the fluid during the SPIF process varied, as shown in Fig. 5. In detail, in Fig. 5a is shown the back side of the GFRP plates for the four configurations studied. These analyses were performed by setting different back pressure levels, from a low back pressure of 0.01 MPa to a high back pressure of 0.2 MPa. The quasi-isotropic configuration, i.e. [0/45/-45/90]s, is characterized by a uniform deformation along the main directions that preserves the circular shape of the section as a trajectory imposed on the tool. With regard to surface defects, the wrinkles appear along the conical side with an out-of-plane deformation that has to be taken into account. Furthermore, looking at Fig. 5a, the presence of the PP frame allows for a constant thickness of the laminate with a variation in thickness, only in the portion made of PP, correlated to the imposed back pressure. In Fig. 5b, on the other hand, the cross-section profiles, extracted from the composite and the metal plate, have been superimposed for all the back pressure configurations studied. These profiles were related to the ideal profile of the truncated cone, which is considered a reference with respect to the imposed tool path. A consistent overlap was observed for each configuration, leading to the conclusion that the low back pressure of 0.01 MPa provides adequate support to allow the composite to adhere to the metal. This can be justified considering the very low mechanical properties of GFRP at the imposed operating temperature, as previously reported in Table 2.

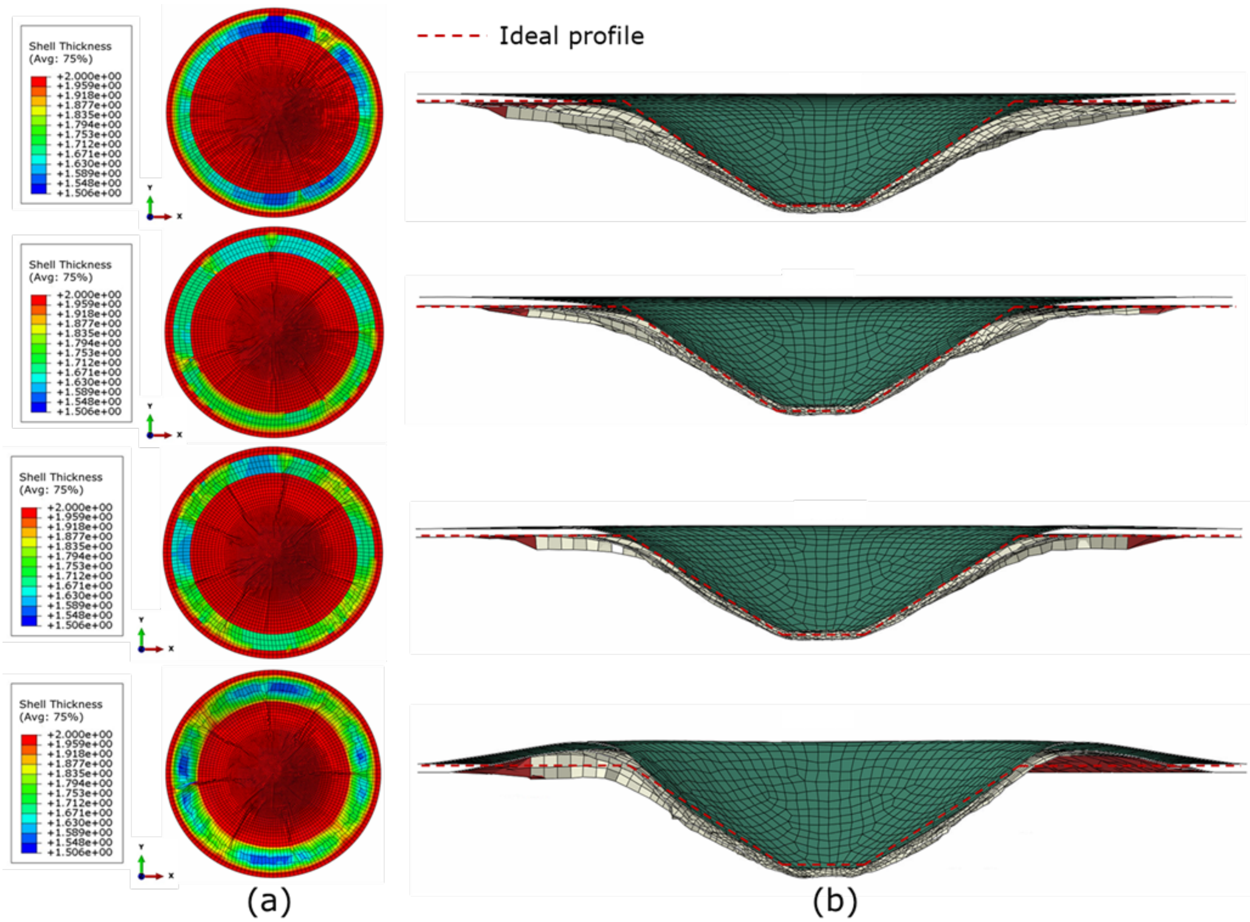

Fig. 5 - Comparison of (a) thickness distribution and (b) shape accuracy for an imposed back pressure for the panel configuration studied. Looking at the Fig. from the top, the back pressure is set at 0.01 MPa to 0.2 MPa at the bottom.

Conclusions

CFRTPs are high strength, low density and stiffness materials. These properties make them for a wide range of applications. Even if CFRTPs are characterized by many advantages, some drawbacks have to be faced. Firstly, CFRTPs are costly to be produced and manufactured. Flexibility in CFRTPs manufacturing can result in a decrease in cost for customized applications. The SPIF is a process far to be applicable if the sheet to be formed is reinforced by long and brittle fibers. Anyway, the process peculiarities can strengthen the flexibility needed for rapid prototyping and small-scale production, opening new possibilities for the CFRTPs manufacturing industry. For that reason, in the proposed research paper, the design of a specific equipment was detailed. This equipment allows the SPIF to be employed in forming sheets made by CFRTPs with the aid of a pressurized fluid that is also used to heat the polymers maintaining a preset working temperature for the whole forming phase. The process feasibility was verified by numerical simulations for

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different laminate configurations. The next step of the research will be the construction of the equipment comparing the experimental results with those obtained in a simulation environment extracting useful data to improve the model as well as to optimize the process of changing the properties of the CFRTPs to be manufactured.

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