A new approach for forming polymeric composite structures

Abstract

The use of composite structures is increasing constantly in the last years, pushed by advantages of reduced weight and high strength. Moreover, the recent scenario points out a great attention on thermoplastic matrix composites due to their intrinsic recyclability as well for their possibility to re-use and re-manufacturing. However, the adoption of these materials can be further appreciated considering the secondary material workability as far as by demonstrating the possibility to re-manufacture the thermoplastic composite.

The proposed work presents an experimental analysis carried out to investigate the downstream workability of a thermoplastic composite by one of the most versatile and flexible process. Glass fiber reinforced Polyamide 6 is the investigated material and the Single Point Incremental Forming is the implemented manufacturing approach. Since the composite matrix is characterized by a glass transition temperature higher than 50 °C, an external heating source has been necessary to perform the process in “hot” conditions. The process feasibility was fully demonstrated as well as the same was optimized in order to derive proper guidelines that can drive the process designer in the method star-up.

Keywords

Thermoplastic composite
Short glass-fibers
Downstream process
SPIF

1. Introduction

Composite materials are gaining great interest for their application in several sectors, such as in the aircraft and naval ship industry, where there is the need of producing different parts in small batches [1], [2]. Composites are well known for their excellent properties in terms of mechanical strength, reduced weight and stiffness, corrosion resistance, non-magnetic properties. They have been using for replacing both no-structural and structural components, that may also be subjected to impacts. Composite materials are usually shaped through primary manufacturing processes, such as autoclave molding, compression molding, pultrusion and filament winding processes, where temperature, pressure, and process time affect the mechanical properties of the produced components [3]. Researchers in the last decades have been investigating downstream processes for forming composites and for understanding the influence of process parameters and material properties on the outcomes.

Machining operations, such as drilling, orthogonal cutting, turning, belong to the downstream process category and are necessary for meeting dimensional and functional requirements of the composite parts [4]. These post machining operations allow to improve the parts by appropriately setting the tool geometry, the cutting speed, the feed rate and the spindle speed. These latter mostly affect the delamination, while all of them in general can influence the surface and machining accuracy [5]

Drilling, for instance, is a machining operation widely used for assembly structural parts and hybrid structures [6], [7]. Nonetheless, this process can cause mechanical and thermal damages on the composite, as well as delamination. The abrasive nature of fibers makes the machining more complicated if compared with metals, furthermore tool deterioration may occur as well [8], [9].

However, an effective keystone in the design of composites structures is represented by the application of composites based on thermoplastic matrices. Their growing use, in fact, finds wide justification in the not negligible advantage related to their intrinsic recyclability [10], [11], [12]. This aspect and the increasing demand from an industrial point of view determine the request of new manufacturing processes investigation as well as the improvement of the existing ones for producing thermoplastic composite parts [1]. With respect to the thermoset composite, the peculiarities of the thermoplastic materials to be subjected at subsequent manufacturing steps completely changes the way to design both upstream and downstream processes.

Thinking about the thermoplastic composites, new classes of processes may be considered for secondary manufacturing such as the incremental forming one that includes different variants. Strong and Hauwiller in 1989 [13] designed an incremental forming method to manufacture thermoplastic composite laminates. Each pre-consolidated laminate, after heating, was transferred to a forming area and shaped between modular molds. Gutowsky et al. in 1991 [14] curved a composite laminate between two diaphragms pressing it on a single mold (Fig. 1). For the shaping, an infrared heating source was necessary to allow the composite to draw onto the mold. They stated that the forming is mostly related to the part curvature and to the initial fiber placement.

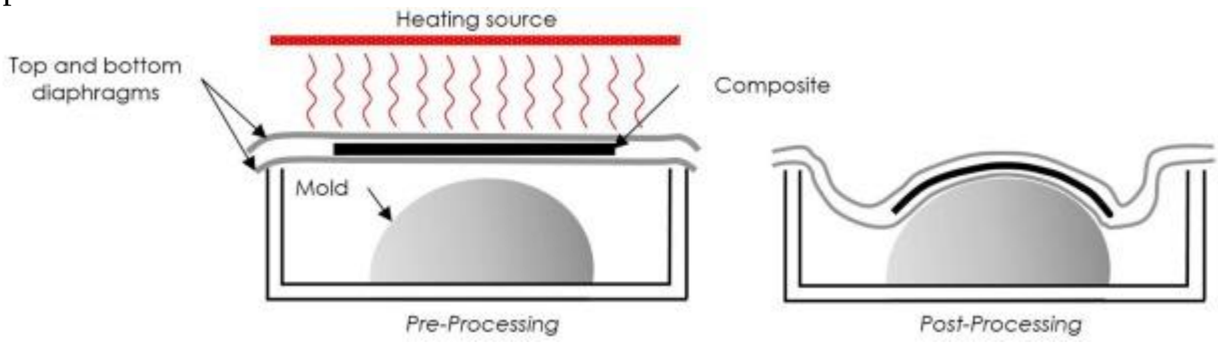

Fig. 1. Composite forming.

The same authors in 1996 patented a method for reducing some deformations, such as wrinkling, that may occur during the forming of the composite [15]. For this aim, they employed a reinforcing structure, such as stainless steel strips, in order to increase the buckling resistance. Another technique was developed by Kaufman et al. [16], according to previous studies [17], [18]. They used a reconfigurable discrete element mold to incrementally form the composite. As shown in Fig. 2, a reconfigurable tool allows to form the desired geometry set by a cam. A locking clam is used to fix the elements and the heated composite is laid between this latter and a diaphragm.

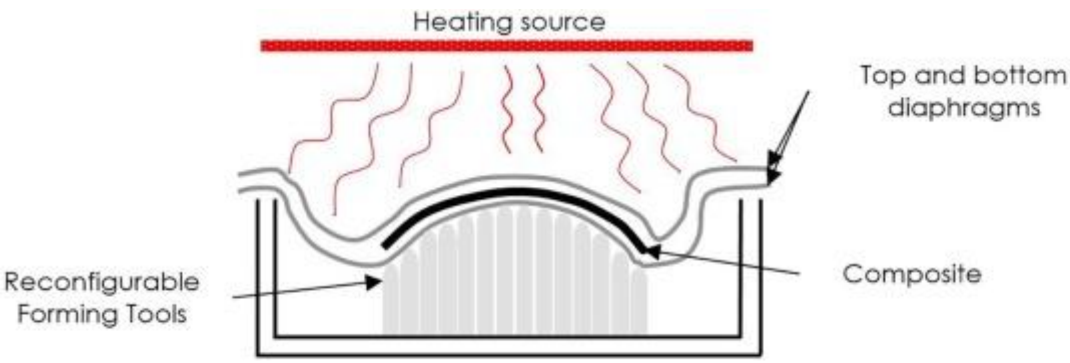

Fig. 2. Incremental forming scheme.

Walczyk et al. [19] investigated a method for producing composite aircraft parts using active tooling. The aim was to form them without dimples or wrinkles. Furthermore the main challenges were to minimize the heating time and to maintain the temperature in the right range during the processing phase.

The general conclusion that can be drawn by the scientific literature is that all the proposed solutions include the application of standard or flexible/configurable tooling. According to that, a relevant technological weakness, related to the time and the cost for the tooling procurement, is not negligible.

A different perspective, although to be demonstrated, can be represented by the Single Point Incremental Forming (SPIF). In general, SPIF is a manufacturing process that allows a plastic and local deformation of a sheet thanks to the action of a tool that moves in all directions according to a path set on the CNC machine. In fact, one of the main point of strength of the introduced technology is that it does not require additional and expensive equipment, but the final profile is obtained just by the deformation imposed on the sheet by a standard hemispherical punch. More deeply, the technology depends on some non-constant parameters, related both to the process itself and to the material [20], [21]. The process, originally used for the manufacturing of metal parts [22], was subsequently extended to the transformation of polymeric materials, which may be processed at lower temperatures [23], [24]. The literature contains examples of SPIFed polymers, such as polypropylene [24], polyvinylchloride [25], polycarbonate and polyethylene [23], poly-lactic acid [26], polycaprolactone [27]. These studies allow concluding that the tool diameter, the step depth, the spindle speed and the feed rate are the main parameters that influence the polymers formability. More recently, Fiorotto et al. [1] investigated a first application of the SPIF on composite laminates. Firstly they tested the manufacturing through incremental sheet forming of complex-shaped molds made of Aluminum to be used later to form composite parts. More in detail, composite plies were placed over the mold and shaped using plastic rollers. Secondly, they tested the direct incremental forming of composite laminates, made of Kevlar and glass fibers impregnated with epoxy resin, using simultaneously diaphragms made of Aluminum and PVC. Diaphragm mechanical failure, quality surface and wrinkling were observed and analyzed. Rimašauskas et al. [28] analyzed also the mold production for composite parts using ISF, mainly when rapid prototyping or customized structures are required. The technology appears to be characterized by low time and cost if compared with traditional processes. Furthermore, the authors analyzed the formability and the surface quality of the molds. Lozano-Sánchez et al. [29] processed by SPIF composites made of a polypropylene matrix filled with different amounts of multi-wall carbon nanotubes. The performance of the outcome was analyzed, showing that a little presence of fibers does not affect the formability and besides an improvement of the mechanical reinforcement is obtained. Furthermore, the color variation on the deformed part and the influence of the thermal effect were also investigated.

In this work, an experimental campaign on a thermoplastic composite, made of short glass fibers and Polyamide 6 matrix, was performed. The target is to assess the Single Point Incremental Forming (SPIF) as downstream process and to analyze the behavior of the material. At this regard, the choice was mainly based on to the possibility of thermoplastic resins to be recycled and, consequently, remanufactured several times [30], [31]. Therefore, the material can be also remanufactured. Details are reported in the section dedicated to the material. As concerns the process, a fundamental advantage is related to the possibility of forming components without using expensive dies and avoiding so long set-up times. Indeed, the setting of a different path allows the manufacturing of a wide number of geometries and makes the flexibility one of the main characteristics of the process. Despite this latter consideration, the SPIF process can be slower than other processes, but it is a good option for producing prototypes and small batches for medical, aerospace and automotive applications [1], [28], [32] as far as it has been demonstrated in past that it is the best solution for parts remanufacturing [33]. Some preliminary tests were carried out on a benchmark profile for a full comprehension of the process feasibility and for the analysis of the microstructural changes in the material. For the purpose of this work, fixed and variable parameters were selected. A lack of quality was mainly measured on the part accuracy. Due to that, a further experimental plan was designed in order to better define the part profile improvement. For this aim, a more complicated shape, a hexagonal pyramid, was tested. Different profiles of temperature, both for the heating phase and for the cooling one, were investigated and microstructural considerations on the composite structure are presented in the following paragraphs.

2. Materials and methods

2.1. Material

Experimental tests were performed on a thermoplastic composite commercially available for producing components for the engineering, as well as for aircraft and automobile constructions. The thermoplastic matrix of Polyamide 6 (PA 6) was chosen for its large use and possible application as laminates. More in detail, PA 6 can be combined with different reinforcements such as carbon fiber, graphene nano platelets or metals [34]. Furthermore laminates made of PA 6 can be vacuum formable or can undergo to downstream working techniques, such as machining and laser cutting, allowing the production of further semi-finished products. For the specific experimental investigation, the Polyamide 6 matrix was combined with short glass fibers having a volume fraction of 12%. The considered composite results characterized by a thermal melting range centered at about 230 °C and a short-term service temperature of 180 °C.

The main mechanical and thermal properties of the used material, as provided by the supplier, are presented in Table 1. All the tests were performed on 150 × 150 × 1.1 mm specimens.

Table 1. Fiberglass reinforced polyamide 6.

Properties	Value	Unit
Density	1.22	g/cm^3
Yield stress	105	MPa
Tensile modulus of elasticity	5400	MPa
Service temperature, long term	−20 ÷ 140	°C
Service temperature, short term	180	°C
Heat deflection temperature	190	°C

2.2. SPIF equipment

As already mentioned above, SPIF is a technology for manufacturing parts, starting from a sheet, through the action of a punch, which locally and plastically deforms the material. The geometry is set on a CNC machine and the punch follows the fixed path moving on the three directions [35].

Fig. 3 shows the equipment designed and manufactured for the aim of this work. A thermal isolated chamber was necessary since an electric resistance of 2 kW was installed and connected to an external control unit in order to heat up the air and to reach the glass transition value, allowing therefore the deformation of the material. A first thermocouple was put inside the chamber to set the temperature from the external unit and a second thermocouple allowed the monitoring of the temperature on the upper surface of the material through a hole drilled on an Aluminium sheet support.

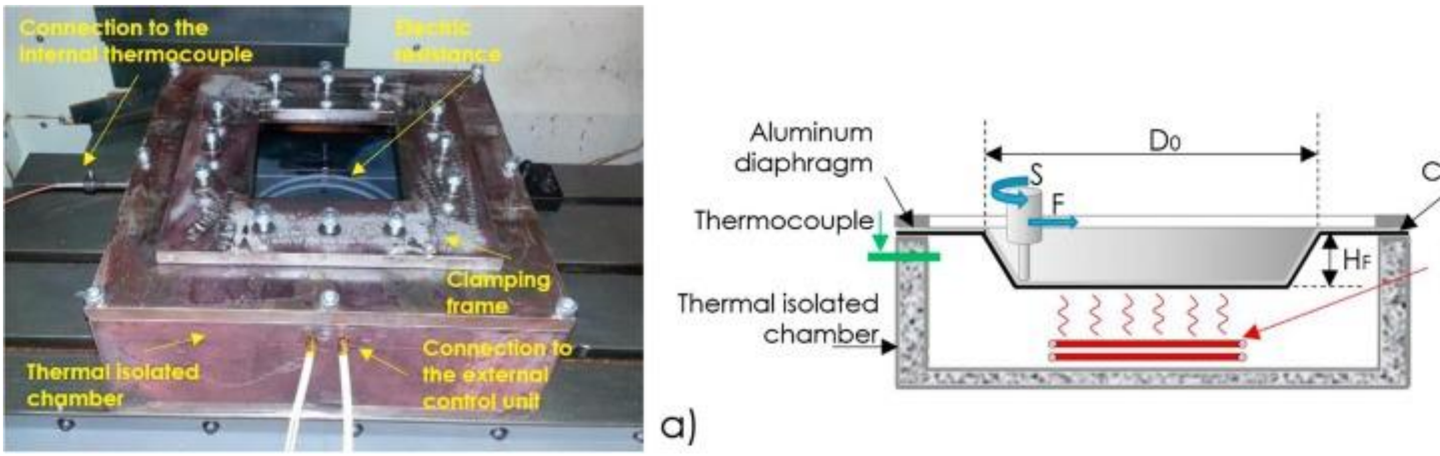

Fig. 3. a) SPIF equipment and b) simplified sketch of the process operation.

Considering this sheet support, it has to be highlighted that preliminary attempts were performed with the punch in direct contact with the worked material. However, worst surface conditions were found [36], thus confirming the necessity of a diaphragm at the interface punch-blank. For this reason, the assistance of an additional low-cost material blank at the interface was introduced. This additional material facilitates the process and drives the composite manufacturing. All the experiments were so carried out superimposing an Aluminum AA1050 sheet (150 mm × 150 mm × 1 mm) on the composite one (150 mm × 150 mm × 1.1 mm) and manufacturing both simultaneously. A hemispherical tool with a diameter (D_p) of 10 mm was used for the tests and mineral oil was applied as lubricant. Finally, all the experimental investigation was performed with fixed values of spindle speed (S = 100 rpm) and forming velocity (F = 5000 mm/min). These process parameters were set by considering both process [33] and material [36] characteristics.

2.3. Morphological analysis

Scanning electron microscopy (SEM) provides high resolution micrographs of surface details at different length scales. SEM scans are generally performed post-mortem (after sample fracture) or after destructive surface preparation protocols. In the case of Short Glass Fibre Reinforced Polymers (SGFRPs), post-mortem SEM micrographs have long been used for inspection of local fibre dispersion, cohesive quality of fibre/matrix interface and ductility or brittleness of fractured facets [37], [38].

In this work, morphological observations were performed by using a field emission scanning electron microscope (mod. FEI QUANTA 200F) on surface and along the thickness of specimens previously coated with a thin layer of a gold-platinum alloy. Micrographs were captured operating in high vacuum conditions at the voltage of 20 kV.

2.4. Accuracy analysis

After the manufacturing, the shape of the SPIFed components was acquired by means of a 3D Minolta Laser Scanning System. The worked surface was matted and made able to be recognized by the laser beam (Fig. 4). Doing that, it was possible to compare the whole surface with the ideal profile. The cloud of points obtained by the 3D laser, in fact, was uploaded into a virtual environment and aligned to the 3D ideal profile. In this way, for each test, the punctual geometrical errors and the relative average value were quantified and measured as the orthogonal minimum distance between each point and the ideal surface. Implementing this strategy, a careful investigation on the part accuracy was addressed and a subsequent experimental investigation was additionally performed to optimize the process outcome.

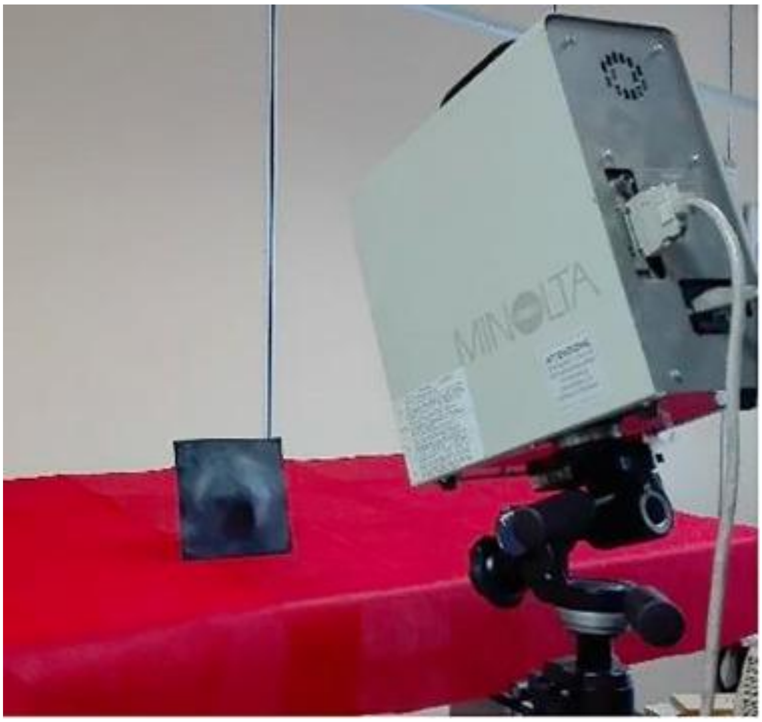

Fig. 4. 3D laser scanning set up.

3. Results and discussion

3.1. Process feasibility

A preliminary experimental investigation was performed to assess the actual process feasibility. A benchmark profile was preferred for this set of experiments and a frustum of cone, with a major base (D_0) of 130 mm and a final depth (H_f) of 30 mm, was adopted (see Fig. 3b). During the first experimentation, changing values were established for those process parameters that mainly influence the formability according to previous investigations [36]. In particular, the wall inclination angle, the tool depth and the process temperature were chosen according to the values reported in Table 2. The composite blanks were manufactured by imposing always the same thermal cycle. More in particular, each sheet was firstly heated by imposing a heating rate able to ensure the desired temperature in about 10 min; after that the temperature was kept constant during the forming phase and then the simple air cooling was adopted before unclamping the part. A full orthogonal plan was performed, that implies 8 (2^k were $k = 3$ factors number) different configurations, each one repeated three times to ensure the robustness of the results.

Table 2. Investigated parameters.

Parameter value	Low	High
Wall angle [°]	30	40
Tool depth [mm]	1	2
Temperature [°C]	150	200

The summary of the experimentation, in terms of process feasibility, is schematically summarized in Fig. 5. As it can be observed, all the investigated configurations return sound parts with exception of the test characterized by high value of the wall angle (α = 40°), low temperature (T = 150 °C) and 1 mm of tool depth. In this case, all the replications returned a broken component and a crack propagation appeared at the end of the process due to the combination of small value of tool depth and low temperature. Actually, the broken typology is different than the one typically highlighted on SPIFed parts. Generally, the crack in SPIF process proceeds tangentially to the tool path, whereas in this case, the composite results "ripped" and the crack spreads radially. However, the different behavior can be justified by the presence of the aluminum that stretches the composite circumferentially bringing to the material rupture. Furthermore, the interposing of the metal sheet between the punch and the short glass fiber composite provides the required stiffness to avoid wrinkles. These were, instead, observed in previous performed researches due to the tool that moves in direct contact on a material, characterized by a viscoelasticity behavior strongly dependent on the temperature of test and on the rate, which the polymer is deformed at [23].

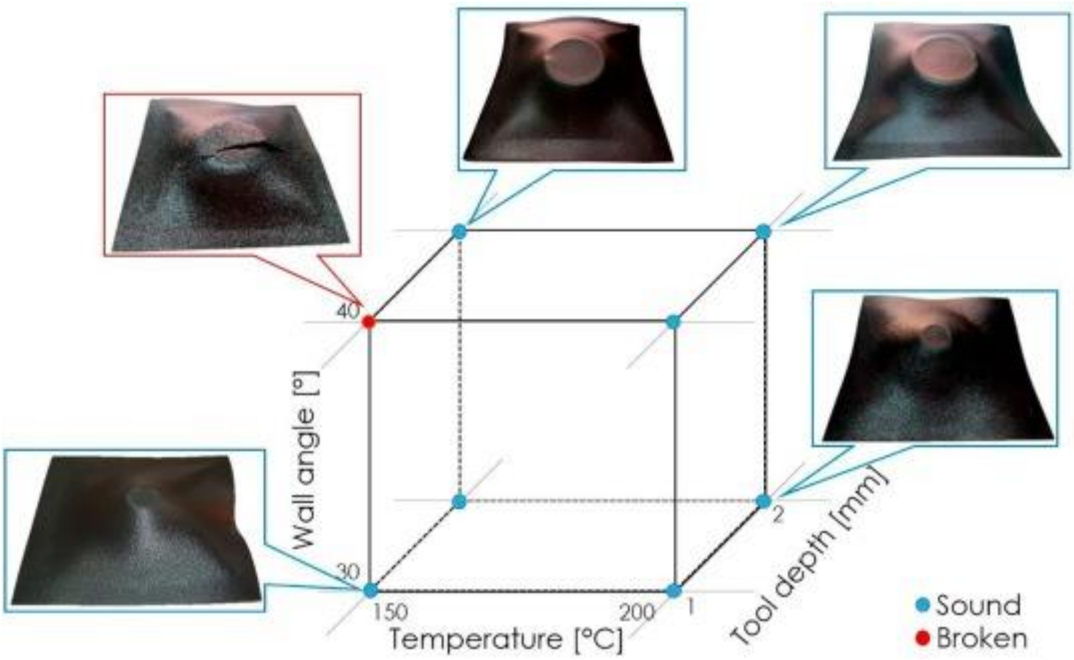

Fig. 5. Summary of the process feasibility according to the experimental plan.

In addition to the macroscopic observations, the parts main characteristics were analyzed in terms of thickness distribution and maximum depth: average and minimum thicknesses as well as the final height reached after the unclamping phase were measured. These results are summarized in the next figure (Fig. 6): here, the higher is the part depth, the higher is the thinning phenomenon. This implies that permanent deformations result more evident when the material stretching increases or when, thanks to the high value of temperature, the material is freer to flow and to adapt itself at the shape imposed by aluminum and punch. However, also starting from this preliminary observation, the poor accuracy on the parts cannot be neglected. In fact, the final depth of the samples results less than 25 mm for the 60% of the investigated cases.

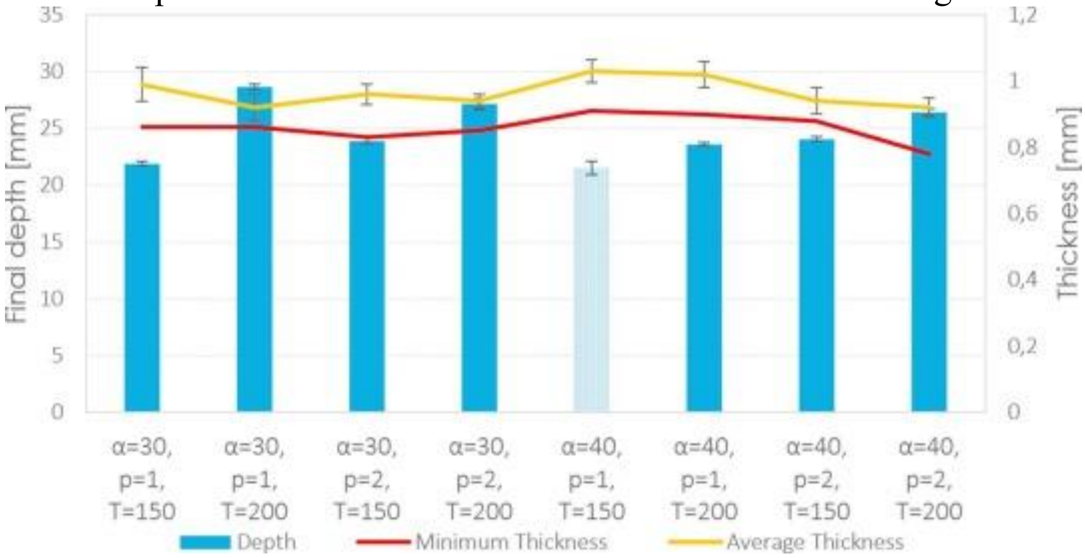

Fig. 6. Final depth and measured thickness.

3.2. Morphological analysis

Morphological investigations by scanning electron microscopy observations were executed to highlight the initial orientation of the glass fibers embedded in the polymeric matrix (benchmark). The images of both the surface and along the thickness of non-deformed and formed polyamide based composite samples were caught to verify how process parameters may affect the glass fibers or degrade the thermoplastic material. More in detail, the as-received conditions were firstly investigated to evaluate the effect of the secondary operation on the glass fiber reinforced composite. The microscopic analysis on the surface of the sample (Fig. 7a) showed the main orientation of the fibers determined by the primary manufacturing process (sheet extrusion), whereas a random distribution of fibers was detected along the thickness as demonstrated by Fig. 7b. This latter highlights also the measures of the fibers diameter repeated along the whole section in order to quantitatively check potential fiber changes after the forming phase.

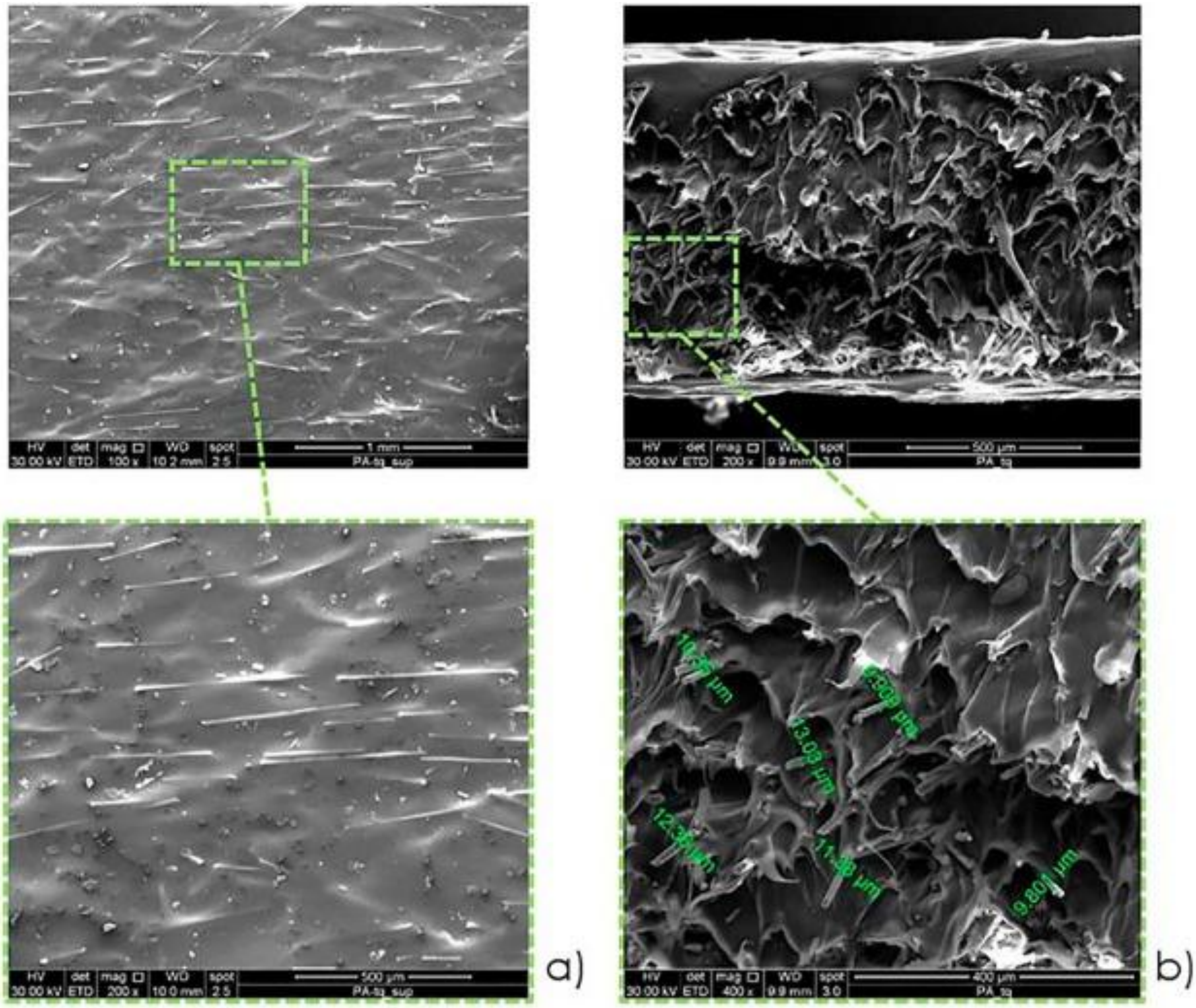

Fig. 7. SEM images of the as-received material a) on the surface and b) along the thickness.

The SEM analysis was performed on the worked components too and, for all the investigated cases, no alteration of the material or distortion of the fibers were observed. To better show this result, the same images are reported in Fig. 8 for four configurations, considered as the most significant because these can fully represent the effect determined by the changing factors. All the surface images clarify that the process does not alter both the matrix and the fibers. The last ones, in particular, maintain their average diameter as well as the initial distribution. More in particular, by using the SEM images, the average value of the fibers diameter was measured taking into account a significant statistical cross section on both the as received and the worked material (Fig. 7b). In all the measured cases, the average value was constant, with a percentage error that is dependent on the measurement tool precision. At the same time, the qualitative comparison between the outer parts surface (Figs. 7a and 8) does not highlight any alteration in the fiber distribution, which results the same between the pre- and the post-formed conditions.

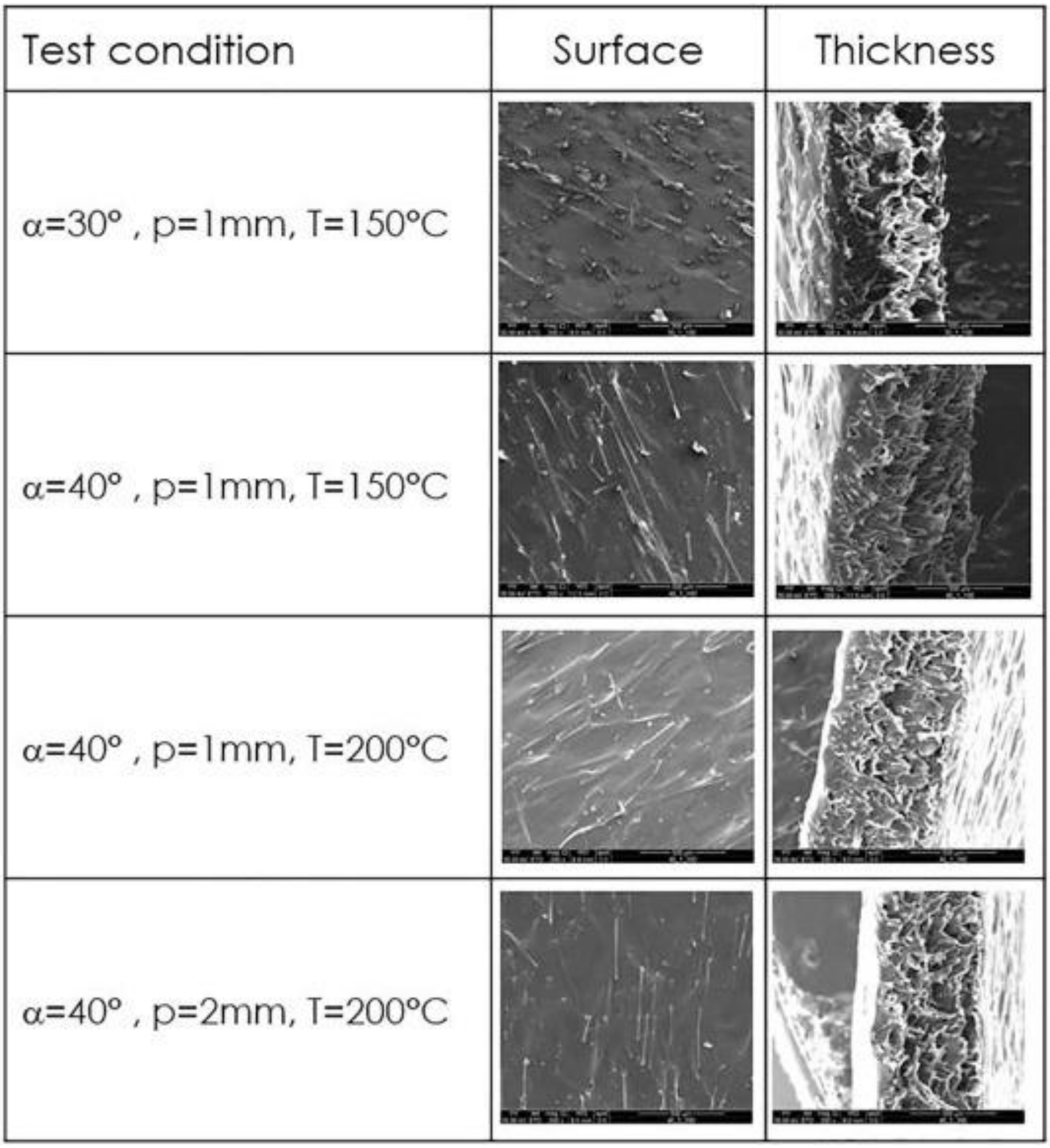

Fig. 8. SEM images of the worked material.

This positive consideration was further supported by researches carried out by means of infrared spectroscopy measurements in attenuated reflection mode on as received and molded regions of examined sheets. These researches evidenced the absence of molecular degradations because of the applied thermo-mechanical stresses and, therefore, encourage the use of SPIF technology in the composite sheet forming.

3.3. Accuracy strategy improvement

Beyond the formability, the preliminary analysis, performed on the benchmark geometry, highlighted relevant distortion of the profile, both in terms of final depth reached and shape accuracy. An example of the assumed concern is visible in Fig. 9, which refers to the following test conditions: α = 30°, p = 1 mm and T = 150°. The geometrical error map on the left (Fig. 9a) and the direct comparison between ideal (continuous line) and real profile (dotted line), acquired by the 3D laser scanning system, on the right (Fig. 9b) are reported. A significant geometrical deviation between the two profiles is present, especially on the lateral surface, with an average geometrical error of 2 mm.

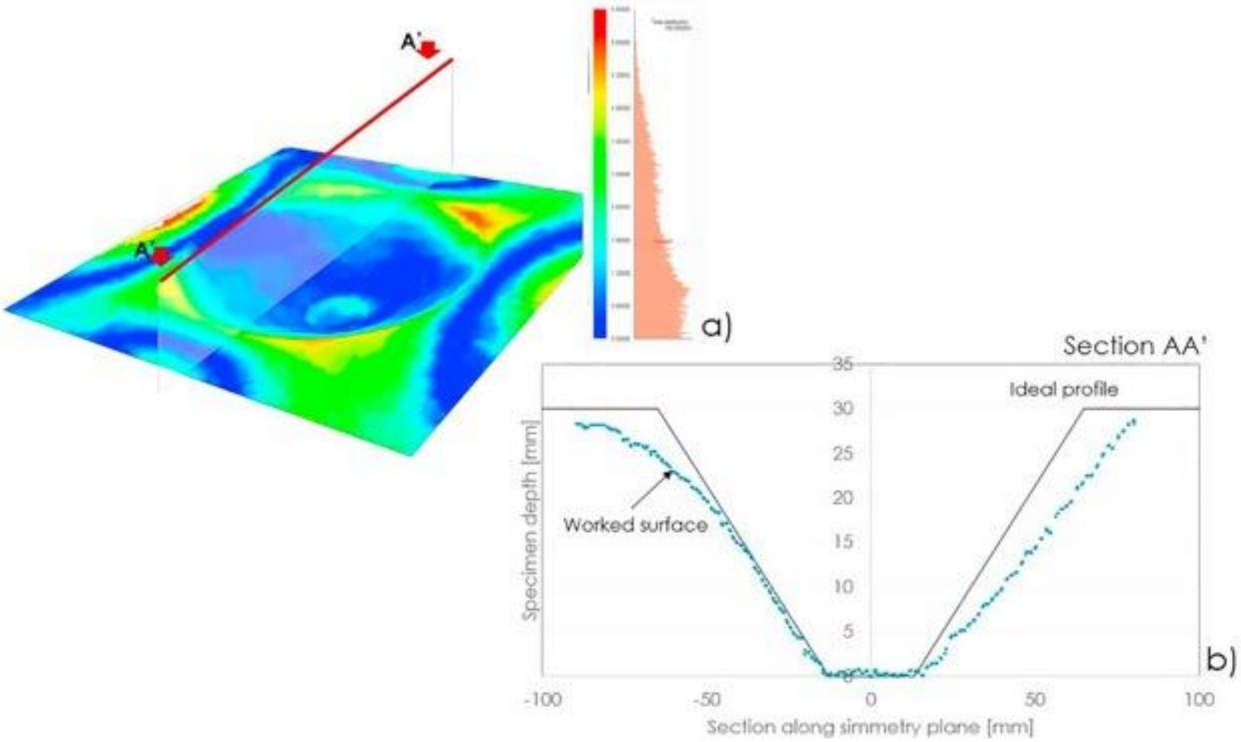

Fig. 9. a) Geometrical error map and b) direct comparison along a section between the worked surface and the ideal one.

This inaccuracy can be explained by several reasons. First, springback and residual stresses have to be taken into account also working composite, because stretching remains the main deformation mechanism. Secondly, the absence of the backing plate determines a variable behaviour of the material, which results freer to bend if the manufactured part is farther from the clamping equipment. Finally, the imposed thermal gradient can affect the material behaviour, making it softer or stiffer. All these effects need to be analysed and reduced for a full process design. According to that, a subsequent experimental investigation was performed aimed at evaluating in deep the part accuracy and how this can be improved by the process optimization.

To make a broad analysis, a more complex shape was chosen based on a hexagonal pyramid with a lateral wall angle of 40°, a major diagonal of 130 mm and a final depth of 40 mm. For sake of coherency, a backing plate was added this time to the equipment to properly lock the bottom part of the sheet as prescribed by Jeswiet et al. in [33]. The process parameters were kept fixed and equal to one of the worst conditions of the previous experimental investigation (p = 1 mm, T = 200 °C).
Four different thermal cycles were tested to evaluate the effect of the thermal gradient for both heating and cooling phase. These changing conditions were reached by modifying respectively the power setting of the electrical heater and the cooling mode (i.e. air and cold water). Concerning the heating mode, three heating times were established and classified as fast (~5 min), medium (~10–12 min) and slow (~55–60 min). In this way, heating rates, faster and slower than the one previously analysed, were checked. Similarly, the time was measured also for the cooling phase and quantified equal to 15 min for the air cooling and 1 min for the cold water mode. Furthermore, the time duration of the working phase was kept constant for all cases (Fig. 10).

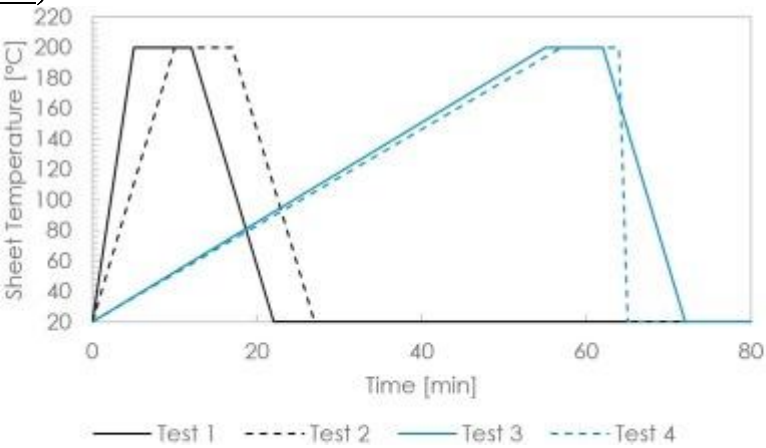

Fig. 10. Thermal cycles used for the investigation.

All the tests brought to sound specimens as expected, but with a remarkable difference in terms of shape accuracy. The latter was punctually evaluated scanning the samples and comparing the revealed shapes with the CAD geometry, as introduced in Section 2.4. In Fig. 11, the obtained formed components on the left and their shape accuracy on the right are displayed. The 3D profile of the first two tests reproduce better the desired geometry, as it can be quantified by looking at the colored maps. The distribution of the geometrical error along the whole profile and the relative average error are graphically represented next to the colored map. The first case (Test 1), characterized by a fast heating and an air cooling, presents the smallest value of average geometrical error (about equal to 1 mm) and the best accuracy. On the other side, a slower heating strongly affects the part accuracy with an increase of the average geometrical error up to 1.5 mm. The worst condition is measured for Test 4, where the slow heating is combined with the fastest cooling (cold water).

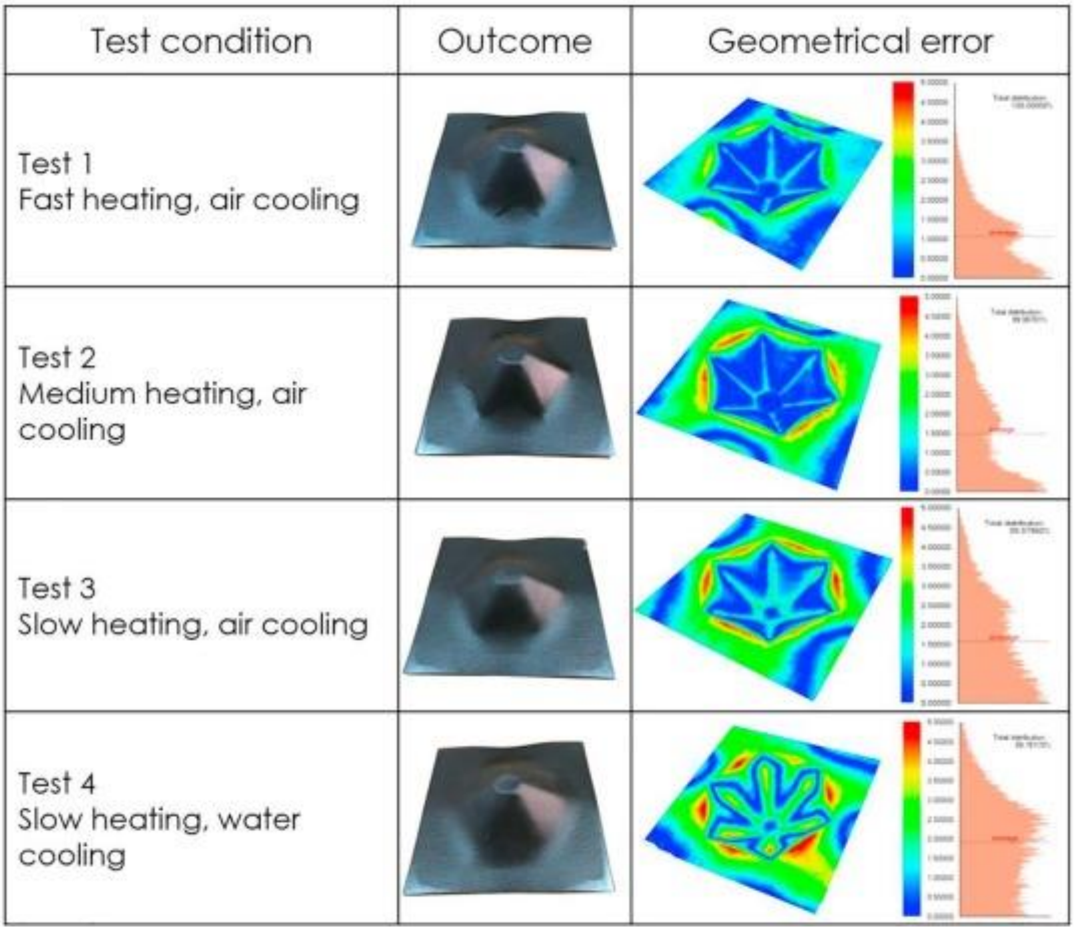

Fig. 11. Results of the accuracy analysis.

Furthermore, the thickness distribution and final depth were measured too. The summary of the results is reported in Table 3. For the thickness measurement, the specimens were previously cut by water jet machine. After that, both thickness and depth were revealed by an optical measurement device.

Table 3. Outcome of the investigated conditions.

Heating mode	Cooling mode	Final depth	Average thickness	Minimum thickness
Fast	Air	40	0.84	0.51
Medium	Air	38	0.85	0.38
Slow	Air	38	0.95	0.56
Slow	Cold water	38	0.95	0.52

Although the evidences in terms of part accuracy, the appearance of small inhomogeneity on the worked product was observed. This effect, considering the previously mentioned absence of chemical and physical degradations of the investigated material, can be attributed to local macromolecular rearrangements that could happen due to both low thermal conductivity and long structural relaxation times, typical of polymers. Moreover, the presence of rigid glass fibers into the plastic matrix could further constrain the macromolecular structure determining the mentioned inhomogeneity visible on the sheet surface.

4. Conclusion

The increasing use of thermoplastic composites opens new perspectives to their application and workability. The possibility to apply secondary processes to these materials, in fact, allows the re-design of the production chain as well as the thinking of the re-manufacturing of composite products. Therefore, it seems urgent to verify the applicability of well-known manufacturing processes to these advanced materials.

According to that, in this study, a promising and flexible technology has been proposed as downstream process in the composite manufacturing chain. A wide experimental investigation on the Single Point Incremental Forming has been performed and both macroscopic (i.e. part soundness, thinning and accuracy) and microscopic (i.e. fibre distortion and polymer degradation) indexes have been evaluated. According to that, it has been demonstrated that the process does not alter the material structure. A subsequent accuracy optimization has been performed on a more complex profile for investigating the thermal gradient effect. The outcome of the second experimental investigation demonstrates the process applicability for the manufacturing of a complex shape as well as the significant improvement of the part geometry working with an optimised thermal cycle, made of fast blank heating and regular air-cooling.

Concluding, the SPIF process can be considered as a valid technological paradigm for manufacturing the thermoplastic composite structures. With respect to the already proposed technologies in the state of the art [13], [14], [15], [16], [17], [18], [19], which implement the use of partial or full dies, SPIF allows not negligible advantages from a production point of view, reducing significantly both the time for the first part and the unit cost. For the same reason, SPIF process can replace or can be used in conjunction to the conventional injection moulding or thermal-forming operations in order to reduce the tooling cost.

Considering the equivalent study performed on metal sheet, some weaknesses of the introduced approach for its scalability to industrial case studies are not negligible and can be ascribed to two factors. First, the SPIF process design results not easier and sometimes it requires an optimisation step performed by a numerical approach. Although the numerical simulation of SPIF process of metal is well assessed, the implementation on composite sheet opens new challenges for the numerical model definition. According to that, an unavoidable future development of the present work will aim at the design of a robust numerical model for the process design and optimisation to real case study. Secondly, it cannot be neglected that SPIF is a promising process for a single part rapid-manufacturing or for the production of small batch. Vice versa, it does not work well when a large production volume has to be performed. This aspect could potentially limit the real scalability to industrial case studies of the introduced approach, but it is also true that the most recent production trends based on flexibility, technology readiness and high products variability principles exploit the SPIF application.

Concluding, starting from the interesting results of the experimental investigation proposed in this study, it can be stated that composite parts can be obtained in a profitable way, both for the first and for the subsequent product use, adopting the innovative manufacturing approach based on SPIF process. The process feasibility was investigated from several points of view. For a full assessment of the industrial process applicability other composite laminates should be tested.