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Imed DERBALI, Pierre OUAGNE, Laurent GUILLAUMAT, Svetlana TEREKHINA - Rapid manufacturing of composite structures made of fabric flax / polypropylene - 2016

# Rapid manufacturing of composite structures made of fabric flax / polypropylene

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**Keywords:** flax / polypropylene comingled fabric, rapid manufacturing, mechanical characterization

## Abstract

One of the major challenges of composites based on a thermoplastic matrix is to fabricate finished parts both in a single processing step and reduced time production. For this purpose, a stamping airflow device is here developed. It permits to produce the V-shaped composite parts made of a comingled flax / polypropylene fabrics only in a few minutes. This is particularly attractive to automotive production. First, preliminary tests and an optimization set of processing parameters are performed. Then, an assessment of the new technical manufacturing reliability of composites compared to mechanical properties of material prepared by a traditional thermo-compression process is presented.

## 1. Introduction

Nowadays, the use of composite materials in industrial fields, especially in the automotive and aerospace, has become indispensable. Moreover, the synthetic fibers used as reinforcement of such materials may be problems if one considers the health and environmental point of view. One of the particular challenges is to replace these fibers by vegetal ones [1-2]. Due to renewable and recyclable resources of thermoplastic matrices, the vegetal fiber composites could help to limit their impact on environment. In addition for mass industry, natural fiber composites could be used for manufacturing the large parts, because of their lightness and good mechanical properties that can be compared to those of glass based fibers [3-4]. Therefore, automotive and aerospace industrials are interested in using cellulose based fibers, thanks to its good forming capacity and mechanical performance. Among the cellulose fibers used as reinforcement of composite materials, flax fibers offer interesting mechanical properties and appear as a green technology solution [5]. Usually, for the fabrication of simple or semi-structural parts, the aligned long fiber reinforced composites must be used. Indeed, for the manufacturing of complex structures, the fabrics are generally considered as the best choice due to their shear capacity in the plane of the membrane [6-7]. Nowadays, only several processes such as light resin transfer molding (RTM light) or thermo-compression are considered by the automotive industry for the manufacturing of thermoplastic based composites [8-11]. However, there is yet a lack to assure both the best rates of automotive production (few minutes per part) and a good quality of complex parts realized in a single operation.

The comingled fabric could be promising for the thermo-compression process because of the possibility to obtain the complex parts in one operation. However, this process is always limited by low production rates. Recent developments in this field for aiming to reduce production time and maintaining a good quality of parts, show that short carbon fiber / PEEK based parts were successfully obtained only in 35 and 45 minutes at 400 ° C, at melting temperature of the resin[12]. Using a hot press equipped by electrical resistances for heating the assembly (mold and material) and the compressed air for its cooling, is still far from mass industrial interests. Note that the Roctool company has successfully developed a molding process by thermo-compression in a short time and one operation applied to large parts based on thermoplastic composites [13]. Their technique consists in heating both molds and material by electromagnetic induction current and cooling by cold water passing through the specific channels in the mold.

In this study, an experimental stamping airflow thermo-compression device developed at the LAMPA laboratory is presented. It permits to realize in one operation and only 200 s the V-shaped thermoplastic composite parts. The idea consists in shaping the comingled flax / polypropylene fabric at the melting point of resin using hot and cold airflows for a heating and cooling thermal cycles respectively.

The objective of this study is dual: (i) to present the optimized manufacturing process of studied composite at rates comparable to industrial needs and (ii) to assess the reliability of the process through the mechanical characterization of the obtained materials.

## 2. Materials and methods

### 2.1 Materials

In this work, two materials based on flax /PP comingled fabric with different weave architectures, were tested. These materials were kindly provided by DEPESTELE group. A 2 × 2 twill weave fabric (310 g / $m^{2,}$ areal weight) and a satin weave (280 g / $m^2$ areal weight) are used. 300 tex ribbons constitute the warp and weft strands. For both fabrics, the mass fraction depends on strand direction: 39% and 61% for the warp and weft strands respectively.

### 2.2 Methods

### 2.2.1 Process methods

### 2.2.1.1 Stamping airflow thermo-compression device

A special thermo-compression device using airflow for heating and cooling material was designed in the laboratory LAMPA. It is shown in Figure 1. This device consists of two principal systems:

- mechanical one, responsible for stamping the comingled fabric
- and heating one, to heat up the fabric up to the thermoplastic resin processing temperature.

The mechanical system is composed of a punch/die commutable couple. A central pneumatic cylinder controls the movement of the punch and is used for varying the applied pressure. Aluminum plates are used as blank-holders to control both the homogeneous distribution of pressure and temperature transfer. It is possible to modify their position and size.

As for the heating system, the airflow heated by electrical resistance is used for rapid (about 2 minutes) heating of fabrics in the mold maintained under the constant pressure. This system is equipped by two temperature controllers. The first plays the role to hold the desired temperature of material in the mold. The temperature control is assured by a thermocouple situated in the fabric during the process. The second temperature controller is used for displaying the air temperature at the outlet of the heating system.

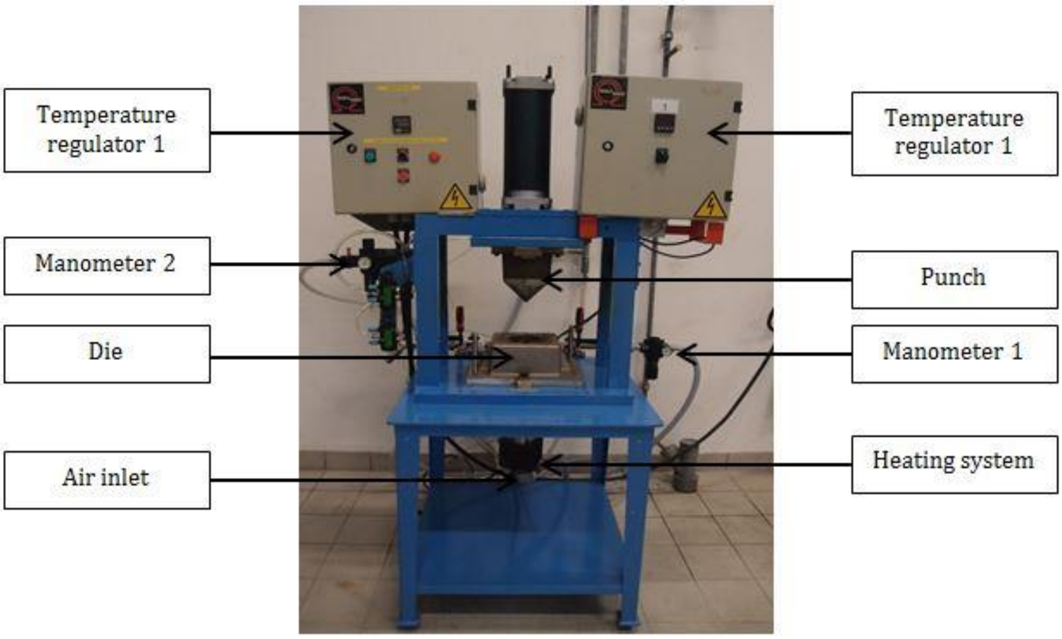
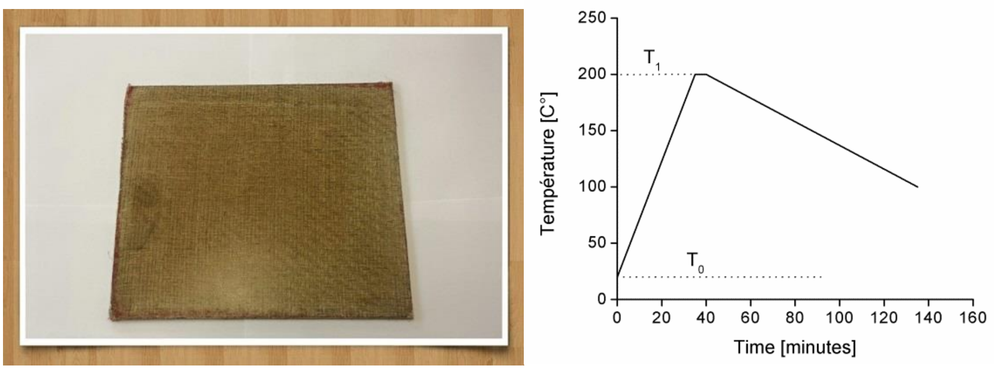


**Figure 1.** Stamping airflow thermocompression device.

The principal of this test consists in rapid heating of a desired number of comingled fabrics layers (180 × 90 mm$^2$) up to 200°C, holding under 5 bar for 1 minute and rapid cooling by stopping the heating system and leaving the cold air to circulate in the mold. As a result, the V-shaped parts are obtained.

### 2.2.1.2 Thermo-compression press

For comparing to a new developed technic, presented above the same fabrics and number of plies were used to manufacture composite plates (250 × 200 x 2 mm$^3$) by conventional hot press. The themo-compression cycle is to hold the samples at 200°C for 5 minutes under 1 bar. Note that the all process takes a lot of time, about 130 minutes, due to the long heating and cooling phases of all considered equipment and material by electrical resistances of hot press. Digital photograph examples of obtained composite and thermal cycle of thermo-compression process are shown in Figure 2. Layers were manufactured by a conventional thermo-compression press with a temperature $T_f$ holding time 5 minutes (Fig. 4).



(a) (b)

**Figure 2.** (a) Digital photograph of composite plate made by conventional hot press; (b) Thermal cycle of this process.

## 2.3 Mechanical Characterization

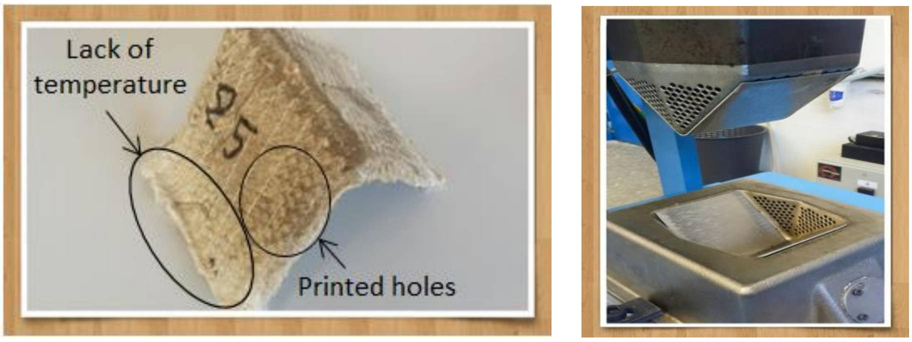
### 2.3.1 Tensile Tests

To determine the mechanical properties of two kind manufactured $[0/90]_9$ flax/PP composite parts and the variability in these properties when different process parameters are used, the tensile tests were realized. A Zwick load frame with a 100 kN load cell is used. The principal strains $\varepsilon_{I}$ and $\varepsilon_{II}$, used for calculations of Young Modulus and Poisson's ratio, were measured by a strain gages and length extensometer. Each test was conducted using a machine cross-head rate of 2 mm/min. Six specimens were tested for each manufacturing condition. The tensile test dimensions of specimens made by conventional thermo-compression were conformed to the ISO 527-4 and -5, whereas the specimens made by stamping airflow thermo-compression were extracted from V-shaped parts and their dimensions ($90 \times 25 \times 2$ mm$^3$) were not conformed. Thus, an additional specimen holder was designed for respecting this norm.

## 3. Results and Discussion

### 3.1 Optimization of new-developed thermo-compression process

The preliminary tests were carried out on composites [0/90] made by new-developed thermo-compression process described in 2.2.1.1 that is composed of 6 to 10 fabric layers. They have shown the capacity of this process to adapt a desired shape of composite (Fig. 3a). However, some geometric defects could be observed on Figure 3a, like the holes printed from mold on the surface of composite due to the airflow conducting or inhomogeneous color of composite due to the gradient of temperature.



(a) (b)

**Figure 3.** (a) Preliminary new-developed thermocompression tests; (b) Optimization mold

In fact, it was found that, during the test two thermocouples situated on the bottom and at the edge of mold show a great difference in temperature. Therefore, based on the obtained results, the mold was equipped by eight thermocouples at different positions. Once again, a great temperature gradient between the bottom and the edge of the mold of about T = 80 ° C was recorded. This could be explained by inhomogeneous airflow: too hot on the bottom and too cold at the edges of the mold.

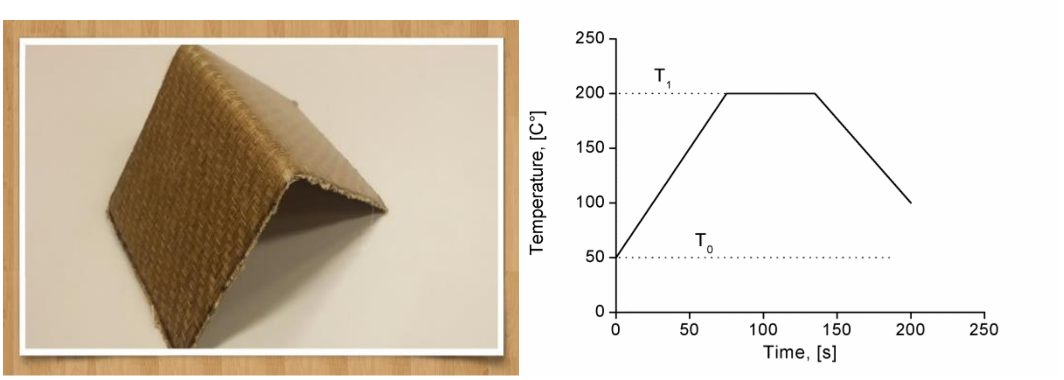
To resolve this problem, the aluminum plates of 1 mm of thickness were placed on the surface of mold for aiming to control both the homogeneous distribution of temperature and prevention of holes on the specimen surfaces (Fig. 3b). Table 1 shows some data of processing parameter optimization used after the mold modification.

**Table 1.** Evolutions of process parameters during the optimization.

| Test | N° of layers | Heating temperature (C°) | Time (s) | | | Air pressure (bar) | | Pressure (bar) | Manufacturing time (s) |
|---|---|---|---|---|---|---|---|---|---|
| | | | Heating up to $T_f$ | Holding | Cooling | Heating | Cooling | | |
| 1 | 9 | 200 | 100 | 300 | 120 | 2 | 2 | 5 | 520 |
| 2 | 9 | 200 | 100 | 300 | 65 | 2 | **3** | 5 | 470 |
| 3 | 9 | 200 | 90 | 300 | 65 | **1,8** | 3 | 5 | 460 |
| 4 | 9 | 200 | 85 | 300 | 65 | **1,6** | 3 | 5 | 455 |
| 5 | 9 | 200 | 75 | 300 | 65 | **1,4** | 3 | 5 | 445 |
| 6 | 9 | 200 | 75 | **150** | 65 | 1,4 | 3 | 5 | 290 |
| 7 | 9 | 200 | 75 | **90** | 65 | 1,4 | 3 | 5 | 230 |
| 8 | 9 | 200 | 75 | **60** | 65 | 1,4 | 3 | 5 | 200 |

As Table 1 shows, the airflow used for heating and cooling is the first parameter that has been optimized. First, an air pressure at the entry of the heater was set at 2 bar for both thermal cycles. The V-shaped composite part was obtained in 7 minutes. Then, the air pressure during the heating and cooling cycles was different. The rising of air pressure till 3 bar during the cooling permitted to increase the cooling rate from 0,84 C°s$^{-1}$ up to 1,54 C°s$^{-1}$. Whereas, during the heating, both the rising time and melting temperature of the resin $T_f$ were optimized using heated air flow. It is evident that decreasing airflow pressure from 2 to 1,4 bar permits the increase of heating rates. Thus, the optimized air flow was set at 1.4 bar. It corresponds to a heating rate of 1.74 ° C s$^{-1}$ that is sufficient to reach the desired temperature of specimen without any heating loss and time. In addition, the optimization of airflow pressure permits to reduce the holding time up to 60 seconds. Finally, by taking into account all varied process parameters, the same V-shaped composite part was obtained in 200 s, twice faster than before optimization.

The Figure 4 shows a digital photograph of 2 × 2 twill weave based V-shaped composite part made by new developed thermocompression device and by using the optimized thermal cycle. The overall shape analysis shows that there are not any geometrical defects, and the surface color of composite is homogeneous everywhere. It is clear that there are not any areas where the resin has not been melted.



(a) (b)

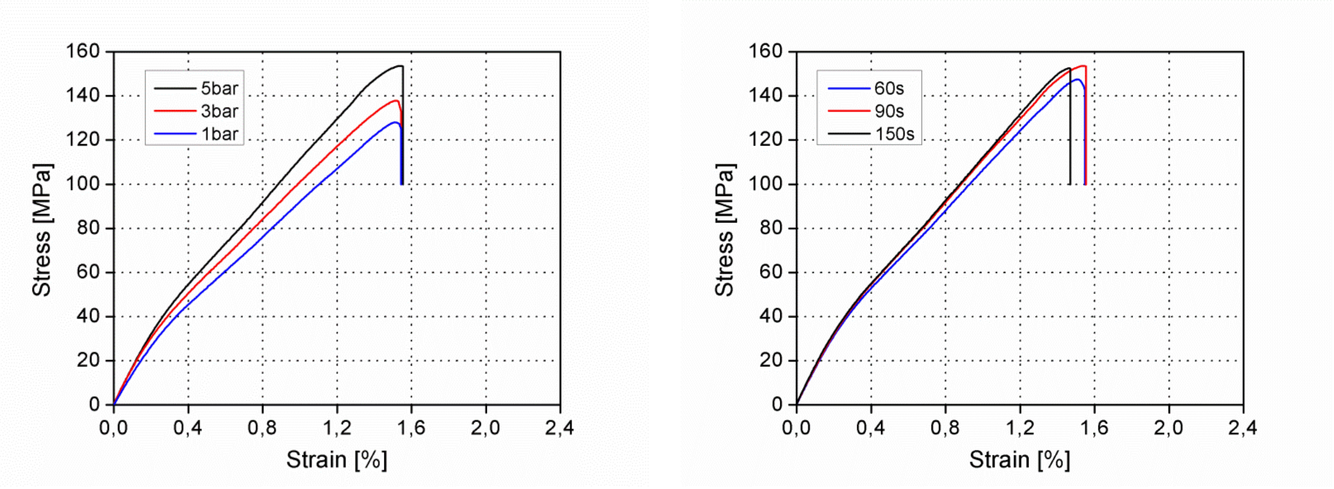
**Figure 4.** (a) Composite part made by new optimized process; (b) Optimizes thermal cycle.

### 3.2 Tensile properties

The tensile tests are realized to show:

- First, the reliability of new developed thermo-compression process;
- Second, the influence of the warp and weft strand direction of satin and twill weave based composites on the mechanical properties after applying the best optimization thermal cycle of new thermo-compression process (5 bar at 200°C for 1 minute);
- Finally, the comparison of mechanical properties between new and conventional thermo-compression process.

The influence of pressure and holding time at 200°C of composite based on weft strand satin fabric is presented in Figure 5.



(a)

(b)

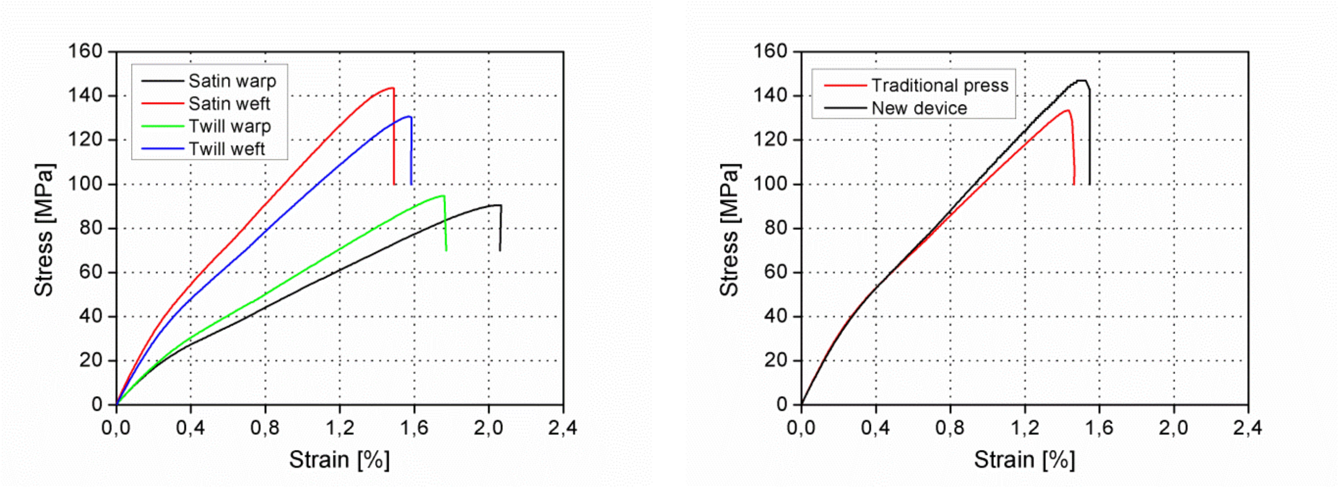
**Figure5.** Pressure (a) and holding time effect (b) at 200°C of composite based on weft strand satin fabric made by new-developed thermo-compression process.

A generally similar bilinear behavior of the stress evolution versus strain for the different pressures is found (Fig. 5a). Note that mechanical properties rise by increasing of applied pressure, the results of which are summarized in Table 2. Thus, the higher pressure is applied, better is the quality of obtained parts due to higher degree of consolidation with a low void content of composite [14-15]. However, no significant difference was observed in the case of holding time (Fig.5b and Table 2). This could be explained by the fact that one minute is sufficient to melt the resin at 200 ° C.

**Table 2.** Tensile mechanical properties of process parameters.

| Holding time (s) | Pressure (bar) | E (GPa) | $\sigma_e$ (MPa) | $\sigma_{ult}$ (MPa) |
|---|---|---|---|---|
| 60 | 1 | 13.8 ± 0.5 | 16 | 127±5 |
| 60 | 3 | 15.7 ± 0.5 | 18 | 137 ± 5 |
| 60 | 5 | 16.6 ± 0.5 | 11.5 | 147 ± 5 |
| 90 | 5 | 16.4 ± 0.5 | 18 | 150 ± 5 |
| 150 | 5 | 16.5 ± 0.5 | 18 | 150 ± 5 |

Figure 6a shows the influence of strand direction in satin and twill based composite on tensile properties. For both kinds of composite, the Young's modulus and the strength at break are about twice higher in weft strand direction than in the warp one. This is due to their difference in mass fraction: 39% and 61% for the warp and weft strands respectively.



(a) (b)

**Figure 6.** (a) Tensile behavior of the warp and weft strands of satin and twill based composites; (b) Mechanical property comparison of two considered processes.

Figure 6b compares the tensile behavior of satin based composites in weft strand direction made by new developed device and conventional hot press for which the all processing times are 200 s and 130 minutes respectively. Both techniques confer to materials the same rigidity. However, the composite made by the new technique is more resistant than the one made by the conventional process because of its slow cooling rate and longtime duration at 200°C. It is known well that vegetal fiber-based composites are very sensitive to temperature. Thus, fiber degradation could take place after a longtime duration at melting temperatures.

Table 3 summarizes the obtained mechanical properties of two strand directions after optimized thermo-compression process by both technics.

**Table 3.** Tensile properties of two strand directions after optimized thermo-compression process and conventional process.

| Process | Material | Stress direction | E (GPa) | $\sigma_e$ (MPa) | $\sigma_{ult}$ (MPa) | $\varepsilon_{ult}$ | V |
|---|---|---|---|---|---|---|---|
| New device | Twill 2×2 | Warp | 9.9 ± 0.5 | 11.5 | 94 ± 5 | $8\ 10^{-3}$ | - |
|  |  | Weft | 15.5 ± 0.5 | 18 | 130 ± 5 | $7\ 10^{-3}$ | 0.15 |
|  | Satin | Warp | 8.8 ± 0.5 | 10 | 90 ± 5 | $1.1\ 10^{-2}$ | - |
|  |  | Weft | 16.5 ± 0.6 | 18 | 145 ± 5 | $6\ 10^{-3}$ | 0.15 |
| Traditional press | Satin | Weft | 16.6 ± 0.6 | 18 | 133 ± 5 | $6\ 10^{-3}$ | 0.15 |

## 4. Conclusions

The main aim of this study is dual: first, reduce the manufacturing time of composite parts based on comingled fabric flax / polypropylene to satisfy the rates of automotive production; and second, to study the influence of optimized process parameters on the quasi-static mechanical properties of manufactured materials.

After the preliminary study and the optimization phase of process parameters, the first objective of our study was attained. The V-shaped composite parts were made in reduced production time (200s). Concerning the second aim, the set of realized tensile tests reveal:

- Importance of applied high compression pressure (5 bar) and optimal holding time (1 minute) during new developed stamping airflow thermo-compression process on the obtained mechanical properties;
- The best rigidity and tensile resistance in the direction of weft strands whatever fabric kind of composite;
- And similar rigidity and the best strength at break in the case of composite made by new developed process compared to the conventional thermo-compression.

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