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Procedia CIRP 99 (2021) 420–425

www.elsevier.com/locate/procedia

14th CIRP Conference on Intelligent Computation in Manufacturing Engineering, CIRP ICME '20

Numerical and experimental analysis of the thermoforming process parameters of semi-spherical glass fibre thermoplastic parts

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Abstract

The thermoforming process is considered among the most promising manufacturing processes for delivering both high quality and volume of thermoplastic composite parts as it exploits all the principal advantages these materials provide. Nevertheless, a series of critical defects may be introduced during the process such as wrinkles, shear deformation of the textile, variation on the thickness as well as geometric distortions and residual stresses which are highly dependent on the material characteristics and the parameters of the process itself. In the present work presented is an analysis of these parameters and their influence on a simple semi-spherical geometry using finite element modelling. The results are also compared with actual experimental results.

Keywords: Thermoplastic composties; Thermoforming; Finite element modelling.

Nomenclature

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GFRTP: Glass Fibre Reinforced Thermoplastic Polymer
R_{Sphere} : Radius of the semi-spherical geometry
Th : Thermoplastic composite materials nominal thickness
v_f : Fibre content %

1. Introduction

In the past few years, in many industrial sectors, the composite materials are being increasingly used. Among them, those consisting of thermoplastic matrix are appealing due to many advantages they demonstrate compared to the thermoset-based composites such as their chemical resistance, their capability of being produced in large quantities and the fact that they are recyclable [1-2]. Among the most promising manufacturing processes for producing thermoplastic based composite parts is the thermoforming. In principle, this process includes the heating of a thermoplastic composite plate up to a temperature close to the melting point, then stamping or draping of the heated plate inside a mould and, consecutively, the cooling down which leads to the final product [3]. During the process though, several defects may be introduced such as wrinkles, undesired variation of thickness, extensive shear deformation of the fibre textile reinforcement as well as residual stresses that influence both the structural characteristics of the product and its aesthetical characteristics [4]. These defects are dependent not only on the drapability and deformability of the composite material at a certain temperature, but also on the auxiliary equipment (tensioners, springs), the stamping speed and the geometry of the stamping tools themselves as well. Even though the analysis of the formation of these defects was made, until recently,

10.1016/j.procir.2021.03.060

empirically by trial and error tests for optimizing this manufacturing process, in the recent years there has been noticed an increasing number of works using the finite element method for simulating the process, and thus, for optimizing it [4-6].

In the present work, presented is a parametrical study of the effect of several parameters such us the orientation of the textile composite, the configuration of the tensioners and the temperature on the formation of wrinkles, the stresses and the thickness variation of a simple semi-spherical geometry. This study includes both finite element analysis using state-of-the-art software while, in parallel, an experimental investigation is conducted for assisting the observation and validation of these phenomena.

2. Experimental

Geometries such as the semispherical ones or the double-domed geometries have been also considered in previous works [6-8]. In the present work, the semi-spherical geometry was considered due to its simplicity on characterizing several induced phenomena and to the fact that is a closed geometrical shape that, most likely, assists the development of defects such as the ones mentioned above.

To this end, the stamping tools of a semi-sphere of R_{sphere}= 49.5 mm was considered. The tools were designed to leave a gap at the total closing of them equal to the nominal thickness of the thermoplastic composite (Th= 0.5 mm) and made of stainless steel. In addition, an infrared lights oven was designed and realized, equipped with two groups of 4 infrared lamps with total capacity of 8 kWatt/h. The distance and the amplitude of these lamps was designed to be regulable. In one facet of the oven is introduced a small window from which the composite plate mounted to the frame can be pulled out and moved between the stamping tools which are mounted on a MTS Universal Testing Machine of 250 kN capacity. This way even the applied force is monitored. The whole configuration is presented in Fig.1.

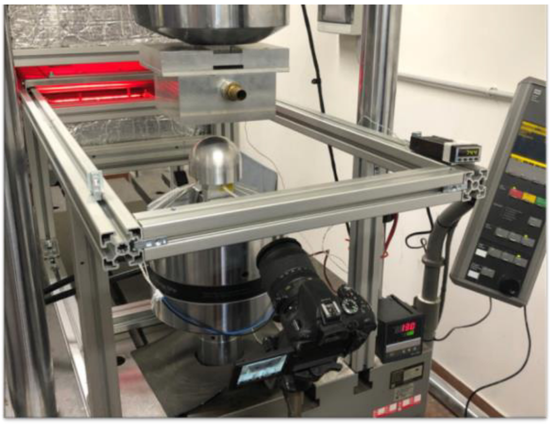


Fig. 1. The machine and equipment used for performing laboratory tests on thermoforming of GFRTP.

Once the composite material is mounted in the frame using the spring configuration chosen each time, is then inserted in the oven in which the heating up ramp is registered using a thermocouple attached to the composite plate. The whole process was calibrated in order not to arrive around the desired temperature in time less than a minute (and thus to apply a certain temperature uniformity on the composite plate). Right after achieving the target temperature, the frame with the heated up composite plate is pulled out in less than 2 sec. time and subjected to the stamping process. The target temperature, known also as the temperature window was previously defined by means of DSC testing and correlation of it with the technical datasheet of the composite materials producer.

The composite material considered is a glass fibre reinforced thermoplastic polymer (GFRTP) of polypropylene matrix. In the present work is denoted as WGF-PP-41.1 as it is an under-development product which the producer wishes to maintain its anonymity. The reinforcing constituent is a twill weave E-glass woven glass textile which has equal amount of fibres towards the warp and the weft directions, respectively. The corresponding v_f is 41.1% in terms of weight fraction while the temperature window for achieving the complete melting of the material starts from 125 and finishes at around 145 °C. Considering the nominal thickness Th =0.5 mm, the composite plate consists of only one layer. A typical heating-up ramp obtained throughout the tests is presented in Fig.2.

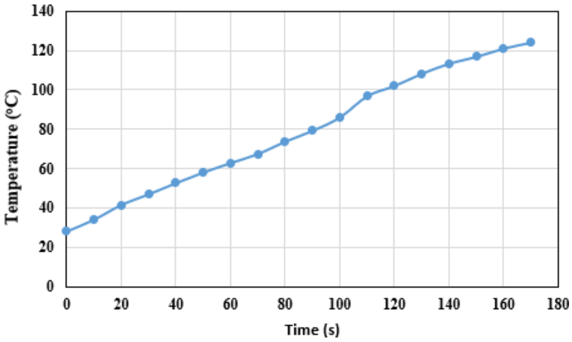


Fig. 2. Temperature-time diagram the heating up of the composite plate

For preventing the formation of wrinkles, it is often needed the introduction of a tension to the composite plate for eliminating the compressive stresses that can lead to the formation of wrinkles. This may be achieved by holding still all the sides of the plate, but this action may introduce a lot of stresses to the composite material while is being formed. A potentially better solution is by fixing the composite plate using a configuration of springs that are placed in the zones that are more susceptible to this phenomenon. In the present work, the efficiency of several configurations of springs is examined. These configurations are presented in Table 1.

Table 1. Configurations of the tested textile plates and the tensioners.

Test	GFRTP plate dimensions [mm]	Angle of direction of the springs-tensioners	Textile Orientation Angle
1	250 x 250	0° – 90°	0°
2	250 x 250	0° – 90°	0°
3	250 x 250	0° – 90°	0°
4	250 x 250	45°	0°
5	200 x 200	45° – edge center	45°
6	200 x 200	45°	45°

The machine cross-sectional speed is set to 5 mm/sec for all the above-mentioned tests. In Fig.3 is depicted a photo of a 250x250 mm composite plate which is perfectly aligned (its principal axis) to the global x-y plane. In addition, the configuration of the springs corresponds to Test 1. In all cases, the springs are mounted to the 4 corners of the plate. In the case of Test 1 are aligned to the principal axis of the composite material.

During the tests execution a high definition photo camera Nikon DS5200 is mounted bellow the male stamping tool so as to observe the deformation of the plate during the process and, thus, to identify any potential wrinkles that are not visible at the end of the tests. A frame during the process is presented in Fig.4.

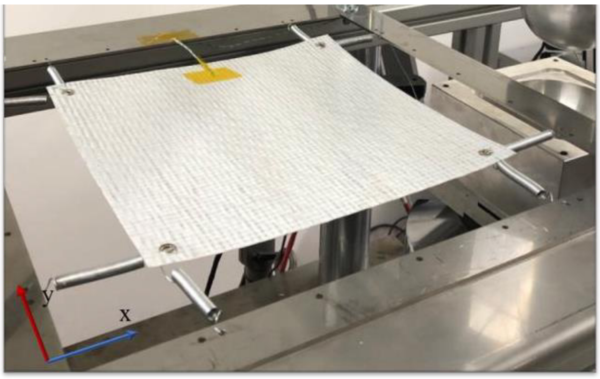


Fig. 3. Configuration of springs and the GFRTP textile orientation compared to the global axis system.

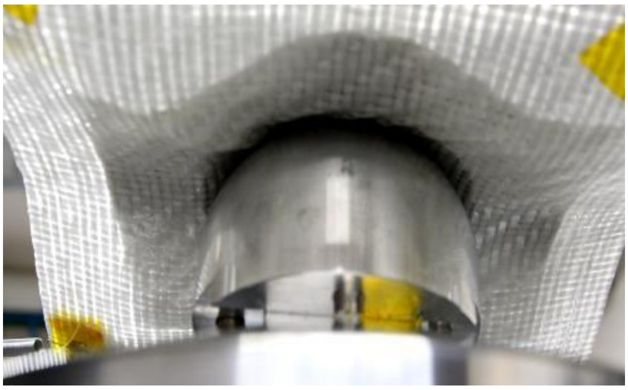


Fig. 4. A frame during the process while the stamping tools are closing.

3. Finite Element Simulation

Considering the time and cost consume of trial and error tests for defining the optimal configuration of the parameters of the thermoforming process, the virtualization of the process itself is gaining credits. Among the existing methods, the finite element modeling and simulation appears to be most promising and to this end there has been used a variety of software such as ABAQUS, LS-Dyna and process specific software such as the AniForm [9]. This one is used in the present work for simulating the abovementioned process implementing in parallel different configurations of springs. The stamping tools and the auxiliary are developed using CATIA V5 software and inserted in AniForm. The material model used is the one of the TEPEX 104 RG600(x)/47% (Bond Laminates GmbH, Brilon, Germany), a polypropylene based glass fibre twill weave composite of 47% vf. Practically, the software utilizes the regression of the output of mechanical tests of in-plane shear and bending for in different temperatures and strain rates to describe the textile deformation. Moreover, utilizes the output of friction tests in several temperatures and testing speeds to characterize the contact between the stamping tools and as well as the friction between the layers of the composite lamina [4-5, 9]. The abovementioned tests were previously conducted in the Netherlands by the Thermoplastic Composites Research Center (TPRC). The stamps crosshead displacement is calibrated at 5mm/s while the temperature was chosen as the lowest possible for the TEPEX (140 ºC).

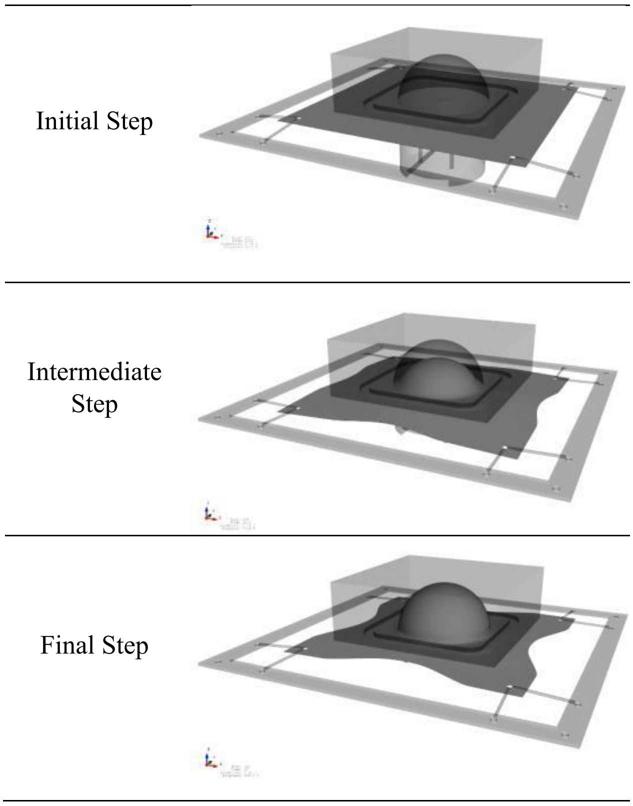


Fig. 5. Three steps of the thermoforming process of the semi spherical shape as seen in AniForm software post processor.

The dimensions of the auxiliary frame are the same as the experimental as well as the dimensions of the composite plate each time. In addition, the springs imposed in the FE model are of k=0.19 N/mm, a value which is consistent with the springs/tensioners used in the experimental campaign. Moreover, the mesh density and size are decided after having conducted a parametric analysis of their effect on the visual and actual results of the simulations. Finally, the gravity effect is also taken into consideration and the corresponding deformation of the plate caused by it is imposed to all the cases. For each model, the computational time requested was about 30 minutes using a standard 4core personal computer equipped with a standard 8GB memory. In Fig.5 are presented are three steps of the simulation of the Test 1. These steps are at the beginning of the process, during and at the end of it.

4. Results

Starting from the experimental results, as seen in Fig.6, the final form of the produced semi-sphere as well as the part of the plate that exceeds the stamping tools are similar.

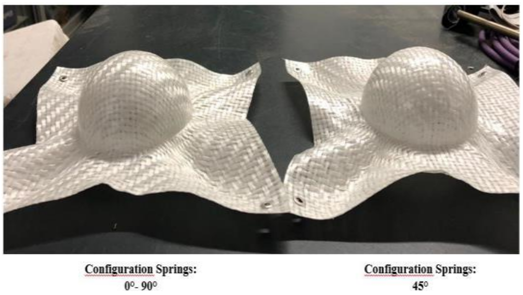


Fig. 6. Semi-spherical products of the experimental campaign of the thermoforming process.

Also, there can be observed the formation of several wrinkles that, after closing the stamping tools completely, are translated into a local overlay of material. Moreover, observed is the deformation of the textile, in terms of relative displacement of the tows.

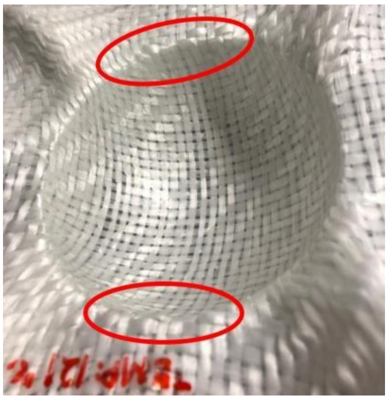


Fig. 7. Details of the textiles local out-of-plane undulations.

As seen in Fig.7, in some areas noticed is an increased undulation (out-of-plane) of the fibres of the textile within the limits of the zones that is developed, presumably, from compressive stresses.

Fig. 8. The shear deformation of the textile in the zone between the springs and the semi-spherical part.

On the contrary, as seen in Fig.8, in the zones between the springs and the semi-sphere, the textile is deformed in a different way, mainly in in-plane shear as a result of the tensile stresses that are developed by the presence of these springs.

In all cases, the force applied by the stamping tools was up to 24 kN with very small variations. A slightly higher value around 25.5 kN was observed in the case in which more springs were added at the edges.

Similar observations extracted from the FE analysis. In Fig.9 presented is the shear angle F1F2 distribution which describes the relative angle between the tows of the woven textile for the 0-90° and the 45° springs configuration, respectively.

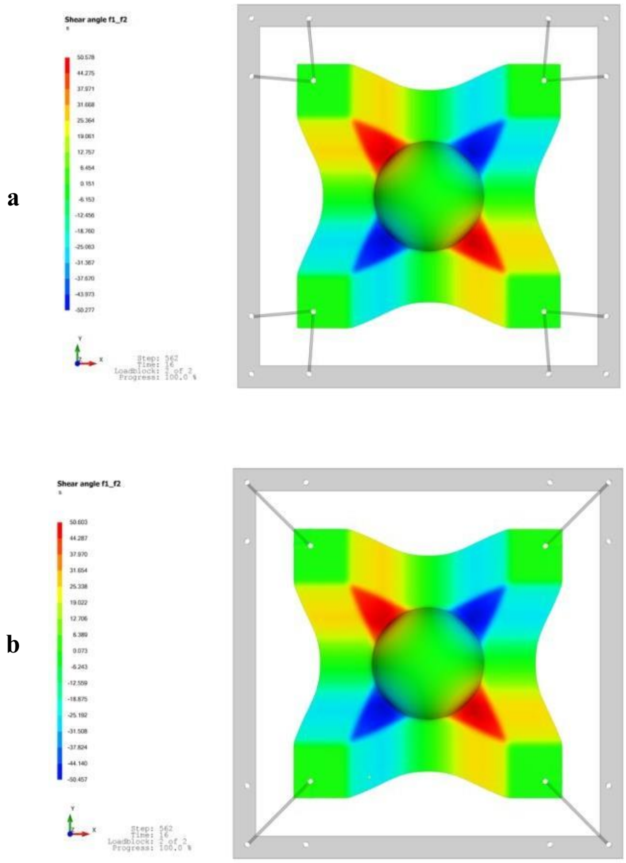


Fig. 9. Deformed shape of the composite material and fiber shear angle distribution for the (a) 0-90° and (b) 45° springs configuration.

The areas coloured red demonstrate highly positive (increase of the angle between the tows) while the blue areas show highly negative values (decrease of the relative fibre angle). These results, with the addition of the stress field at the closing of the stamps, may indicate the regions in which the textile will be deformed and the formation of wrinkles; areas with compressive stresses and negative values of shear angle favour the formation of wrinkles.. In Fig.10, presented are the x component of stress. Similar is also the fiber stress towards the y axis concluding that the two configurations demonstrate similar behaviour and critical zones.

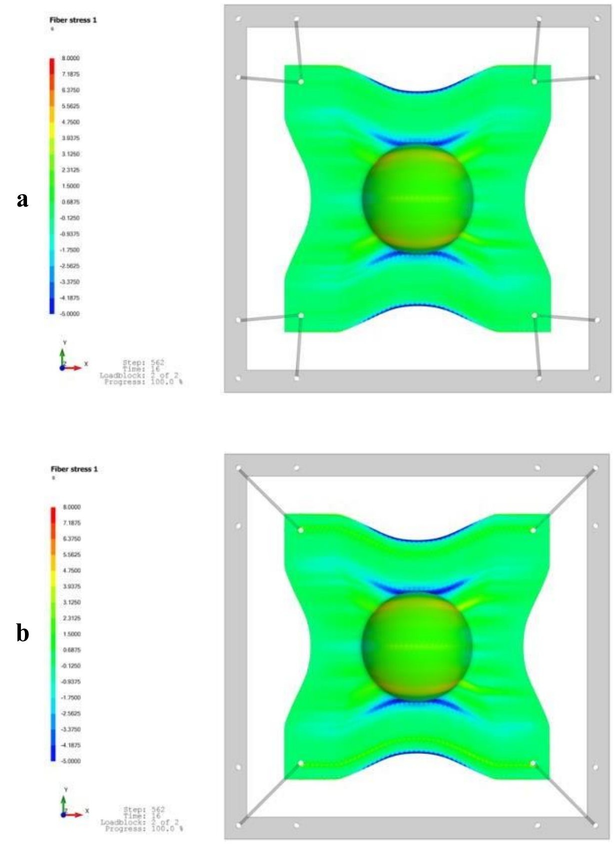
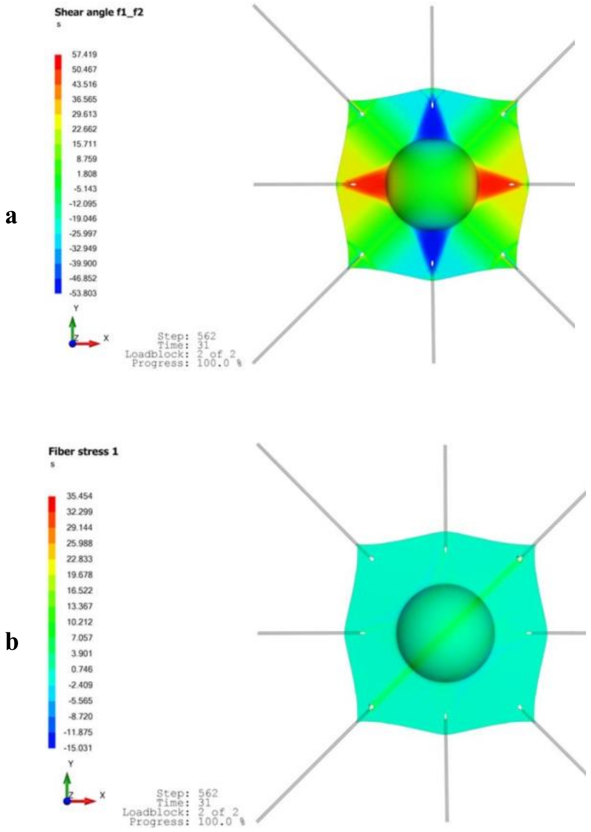


Fig. 10. The fibre stress variation towards the x-axis for the case of (a) 0-90° and (b) 45° springs configuration.



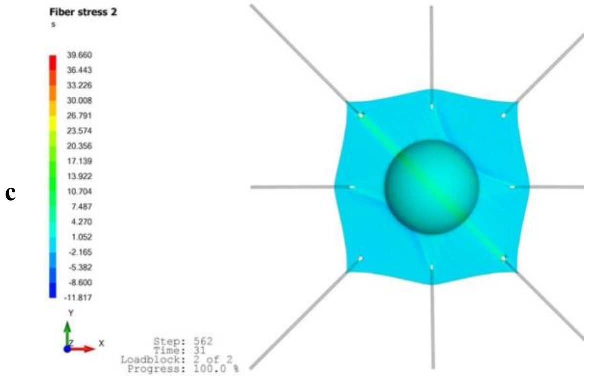


Fig. 11. (a) fiber shear angle F1F1 and fiber stress along the x (b) and the y (c) axis.

It can be seen a compressive stress concentration at some parts near the semi-sphere which can cause phenomena such us undulations and material overlaying. All these results mentioned above are very consistent with the experimental output also for the region of the semi spherical part. By changing the orientation of the textile to 45° and imposing springs at 45° or even at the centre of the edges of the composite plate, the stresses are redistributed as seen in Fig.11. That redistribution of the stresses is presented in Fig.11 (b) and (c) in which even though the maximum values are increased, the spherical part and the zones around it appear to be more uniform compared to the other configurations. The fiber shear angle maximum values (positive or negative) are increased by almost 10% in this case but considering the more uniformly dispersed and mostly tensional stresses appeared, this configuration appears to decrease the formation of wrinkles and other unwanted defects especially at the zone around the semi- sphere.

5. Conclusions

In the present work, it was investigated both numerically and experimentally the effect of several parameters such as the orientation of the textile composite and the auxiliary equipment on the output of the thermoforming process when applied at closed and semi-spherical geometries. For achieving this, developed was a laboratorial working station using a universal testing machine. The phenomena observed experimentally are in great agreement with the output of the FE simulations. This may contribute to the development of strategies to lessen the experimental trial and error tests for optimizing the process. From analysing both the experimental and FE results, there can be seen that the orientation of the tensioners do not influence the output of the process significantly. On the contrary, the orientation of the fibres and the number of tensioners (applied symmetrically) seem to redistribute the stresses introduced while the stamping tools are closing.

Acknowledgements

The present work was partially funded by the national Italian research project C.R.AB (Composites Research Abruzzo) under the auspices of the Region of Abruzzo (Italy) and the European Union (POR FESR Abruzzo 2014- 2020 – ASSE I- Attività 1.1.1 e 1.1.4, contract CAR n.2617- COR n.217245). The authors wish to thank Dipl-Ing. Pierfrancesco Spitilli and Dipl.-Ing.Massimiliano Martella for their assistance on this subject during their thesis.

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