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Influence of the pre-heating process of thermoplastic mono-material sandwich-structures for thermoforming

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Abstract. Continuously fiber-reinforced sandwich-structures are highly used for lightweight design applications. However, with an increasing number of recycling cycles, the fiber length decreases with each cycle and downcycles the material. One solution to this problem is the usage of mono-material sandwich-structures. The reinforcement fibers, the matrix material and the shear-resistant foam core consist of the same thermoplastic base-polymer and enable therefore mechanical recycling without the need to separate the different material components. Within a fusion bonding process the semi-finished products are joint to 2D sandwich-structures. The thermoforming of these materials requires precise temperature control before, during and after forming. The different process steps of preheating, thermoforming and cooling of sandwich-structures causes a time dependent temperature gradient in the direction of the structures thickness [1] while meeting three requirements: the material must be heated above glass transition temperature to enable the forming, while also preventing the foam cells from collapsing and the reinforcing polymer fibers from thermally induced relaxation. To investigate the pre-heating of mono-material sandwich-structures based on Polyethylene terephthalate (PET), four different process routes where compared: conductive, convective, microwave- and infrared- (IR) based. To enable the monitoring of the temperature during the conductive, convective and IR-based processes, thermocouples were introduced into the sandwich-structures bevor the fusion bonding process. They were placed into the foam core and the boundary layer between the foam core and the face sheets at different positions. The temperature control during the microwave-process was implemented by a thermocamera. The formation of the temperature gradient was observed by choosing 130 °C and 170 °C as temperature levels. The cooling behavior was observed by positioning the sandwich-structures between two flat steel plates which were kept at 40 °C. Subsequently, the experimental results were compared within the four process routes: a microwave-based process is not suitable for the preheating of PET-mono-material sandwich-structures, preheating by using conductive, convective or IR-based processes is possible, while conductive and the IR-based process route had comparable, fast cycle times.

Introduction

The escalating global consciousness by policymakers and society, regarding waste management problems and the deficiency of effective recycling strategies is reflected in a multitude of legislative undertakings at a national and international scale. The proposed amendment to the EU End-of-Life Vehicles Regulation [2] serves as a current example, mandating that 25 % recycled plastic, a portion of which must originate from end-of-life vehicles, be used in new vehicles. This necessitates the automotive industry to augment its recycling strategies. Additionally, the reduction of greenhouse gas emissions is a key goal for the automotive industry on their way to more sustainability. Fiber-reinforced polymers (FRP) are due to their weight specific properties a key lever for reducing weight and emissions. However, they show some major challenges regarding mechanical recycling. Herein fiber shortening and therefore reduction in mechanical properties hinder the use in the same application, especially for continuous fiber reinforcements. One approach to enable mechanical recycling of the materials into the same application is the pursuit of a mono-material approach. Therefore, different morphologies of the same base polymer are used, e.g. fibers, foam and compact. By reinforcing the polymers matrix with fibers made of the same polymer, but higher degree of molecular orientation, a self-reinforced plastic can be created.

Principle and processing methods of self-reinforced plastics

Principle of self-reinforced plastics. The principle of self-reinforced plastics is based on the polymer's molecular structures. The energy from covalent bonding within a molecular chain vastly surpasses that of secondary bonds. To harness this effect, a deliberate orientation of the molecules is necessary. The degree of orientation, and consequently the mechanics, can be specifically adjusted through fiber spinning followed by drawing, thereby enabling the use of polymer fibers as reinforcing fibers (Fig. 1). This concept was first introduced by Capiati and Porter in 1975 [3]. Since the drawn state of the reinforcing fibers represents a thermodynamically unstable state, elevated temperatures might induce relaxation and subsequently lower mechanical properties. To counter this, bi-component self-reinforced materials utilizing co-polymers have been introduced to create a slight difference in melting temperature. The Fraunhofer Institute for Chemical Technology ICT, in collaboration with several other partners, are researching the processing of polyethylene terephthalate (PET), biobased polylactide (PLA), and polyamides (PA) using this bi-component approach [4, 5]. Despite achieving high tensile moduli and strength, particularly considering the low density compared to traditional fiber reinforcements, there remains a deficit in mechanical performance [6]. To surmount this obstacle, a sandwich approach can be applied by incorporating a third material morphology in the form of thermoplastic extrusion or particle foams, also derived from the same polymer. Using a fusion-bonding process, all these morphologies can be combined without adhesives to form a mono-material sandwich-structure. The resulting geometric stiffening leads to a significant increase in performance with a minimal increase in mass.

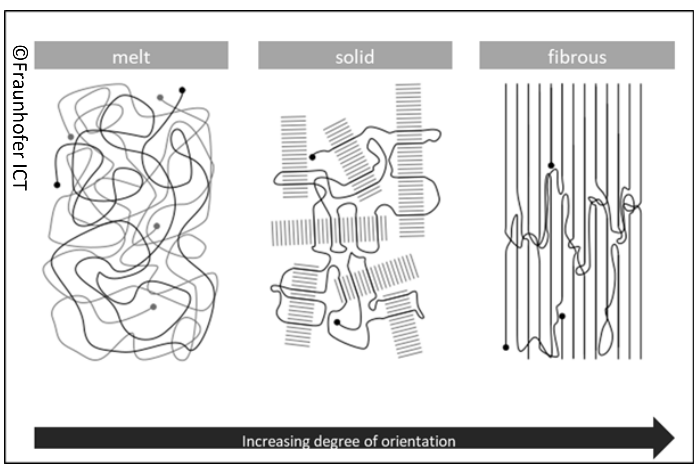

Figure 1 – The principle of self-reinforcement

Processing methods of self-reinforced plastics. To further harness the potential of lightweight design, the proportion of reinforcing fibers can be amplified without influencing the overall density, given that the reinforcing and matrix fibers possess approximately identical densities. Through the application of the sandwich approach and self-reinforcement, properties comparable to those of a conventional FRP can be attained utilizing a single material.

Self-reinforced plastics are distinguished from FRPs not merely in their mechanical properties and structures, but also regarding the requisite processing methodologies. Yet, standard industrial

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equipment can still be employed, provided that the parameters and molding technologies are suitably adjusted. Depending on the foundational polymer, numerous strategies exist to establish a difference in melting point between the fiber and the matrix.

Initially, a commingled yarn is generated from both morphology types, which is then elaborated into fabrics (e.g., woven fabrics) utilizing textile processes. Analogous to conventional laminar composites, the monolithic semi-finished product is fabricated by melt impregnation. To circumvent relaxation - the reduction of internal stress of the reinforcing fibers in the drawn state - the temperature's impact on the material should be minimized throughout all process stages. This principle is also applicable to the fusion bonding of face-sheets and foam core, where excessive processing pressures and temperatures can result in the core's collapse.

The full potential of thermoplastic sandwich composites can only be fully realized through large-scale functionalization procedures such as thermoforming. These processes facilitate the attainment of complex 2.5D geometries with varying radii, wall thicknesses, and degrees of thermoforming. Moreover, the deliberate compaction of the core allows for localized adjustment of the wall thickness and thus the stiffness. Forming is conducted similarly to conventional fiber composites, albeit at temperatures beneath the melting point for the forementioned reasons.

The thermoforming of these materials requires precise temperature control before, during and after forming. The different process steps of preheating, thermoforming and cooling of sandwich-structures causes a time dependent temperature gradient in the direction of the structures thickness [1] while meeting three requirements: the material must be heated above glass transition temperature to enable the forming, while also preventing the foam cells from collapsing and the reinforcing polymer fibers from thermally induced relaxation.

Experimental work

The conducted experiments demonstrate the potential of four different process routes for preheating 2D mono-material sandwich-structures in order to form them afterwards.

Material. For the presented study, srPET face sheets with the product number 50203 (thickness: 1.1 mm) produced by Comfil ApS were used. As a core material a PET-based extrusion foam from Airex of the product category T92.100 was processed (Batch numbers: SBNI022002, SBNI028001, sheet thickness of 10 mm). According to the manufacturer's specifications, the average density of the foam is 100 kg/m^3, with a range of 95 – 105 kg/m^3 in accordance with the standard ISO 845. The thermal conductivity specified according to the standard EN12667 in the data sheet for the T92.100 foam has an average value of 34 mW/m.K at 10 °C [7].

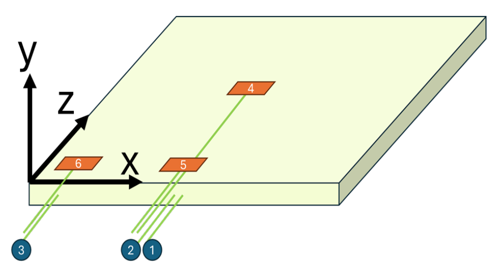

Figure 2 – Position of thermocouples in the final sample

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Experimental setup: Comparison of various process routes. In order to enable temperature monitoring in the following experiments, type K thermocouples were inserted into the foam core and the boundary layer between the core and face sheets before the fusion bonding process. For this purpose, the foams were scored to the desired depth of half the sheets thickness (5 mm) and the thermocouples were placed in the respective position, as show in Fig. 2 and specified in Table 1. The face-sheets and core material were stacked into the sandwich-configuration of one face-sheet on top and the bottom, and one foam sheet in between. The thermocouples which were placed at the boundary layer of face-sheet and foamcore were fixed to their desired position with Polyimide-tape to prevent shifting from their original position during handling of the material. After the fusion bonding in a pressure- and temperature-controlled process, the overall measurement of the 2D plates were 400 mm x 400 mm x 12 mm, they then were cut with a band saw into 200 mm x 200 mm wide samples.

Table 1 – Position of thermocouples

Nr. of thermocouple	**Name of the position**	**Position in mm**		
		x	**y**	**z**
1	Center foam	100	- 6	100
2	Edge foam	100	- 6	20
3	Corner foam	20	- 6	20
4	Center boundary layer	100	-1.1	100
5	Edge boundary layer	100	-1.1	20
6	Corner boundary layer	20	-1.1	20

The considered process routes included conductive, convective, IR-based and microwave-based heating. Each process was carried out, by heating up the sandwich-structure until the center-position inside the foam reached the target temperature. To evaluate different heating rates, two different target temperatures above the glas transition temperature were chosen: 130 °C and 170 °C. Once the target temperature was reached, the sandwich-structures were manually transferred into a plate-shaped mould of a Dieffenbacher 3600 t hydraulic press. Aluminum spacer blocks were inserted to prevent the sandwich-structure from compacting completely by fully closing the panel tool, as shown in Fig. 3. The mould was kept at constant 40 °C. The cooling process was stopped, once the temperature at the foam center reached 50 °C. To prevent the material from sticking to the heating plates/oven grid of the conductive and convective processes, teflon foil (thickness: 0.1 mm – 0.15 mm) and aluminum plates (thickness: 2mm, starting temperature at room temperature) were put on both sides of the sandwich-structures during the conductive heating and at the lower side during the convective heating. During the transfer into the mould, both the foil and the plates were removed.

The process routes were carried out as follows:

- Convective heating: Fan oven which was kept at the material's target temperature plus 10 K
- Conductive heating: Contact heating table, heating plates were kept at the material's target temperature plus 10 K
- IR-based heating: IR emitters were set to the target temperature plus 5 K
- Microwave-based heating: Varying microwave field strengths and powers were used

Sandwich-structures which were used in the microwave-process were not equipped with thermocouples but observed with a thermocam.

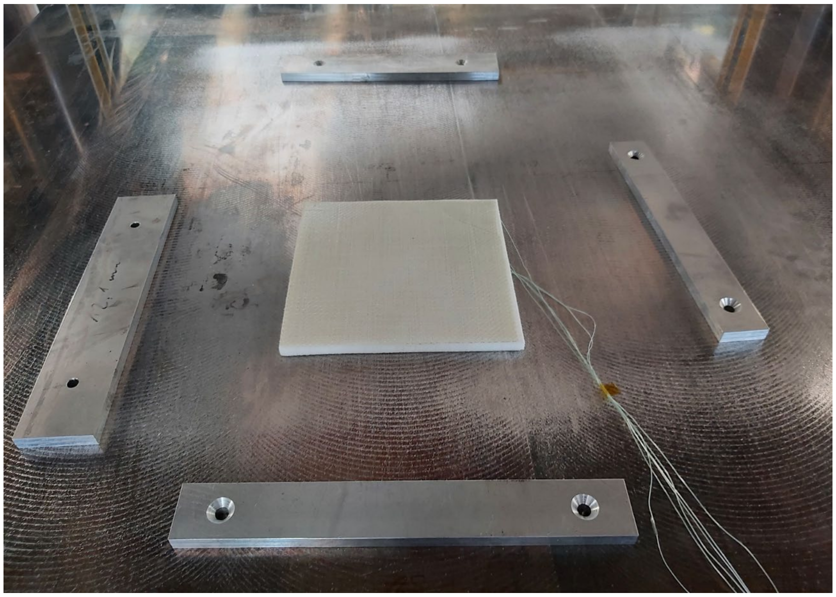

Figure 3 – Set-up of the press-mould with spacer blocks and sandwich-structure including thermocouples

Results and discussion

The following diagrams show the observed temperature profiles for the different processes and target temperatures (Fig. 4). No significant influence of the edge- and corner positions, neither in the boundary layer or the foam, can be seen within the temperature profiles. Pre-Heating within a microwave-based process was not possible, since the microwave did not sufficiently couple into the material and no temperatures above 70 °C could be reached with a power of 2.1 kW – 16 kW and varying times from 30 s – 180 s. Convective, conductive and IR-radiation are suitable to reach the target temperatures. None of the processes caused material damage like fiber relaxation, foam collapse or delamination of the face-sheets from the foam core. The convective process enables a homogeneous temperature distribution over the heating time, whereas a much more pronounced time-dependent temperature gradient in the thickness direction of the sandwich-structure can be observed in the other processes. It is interesting to observe that the final temperature of the foamcore during the IR-based heating was higher than the maximum reached temperature in the boundary layer. This can be caused by a superposition of the radiation from the top and bottom of the sandwich-structure. Fig. 5 shows a direct comparison of the different processes on the center position of the foam and boundary layer. Convective heating shows the longest cycle time, while conductive and IR-based processes show comparable fast cycle times, as shown by the mean values of the heating and cooling times in Table 2. The comparable high standard deviation based on the total time-value of the conductive and IR-based processes can be reasoned with the shorter overall heating times compared to the convective process.

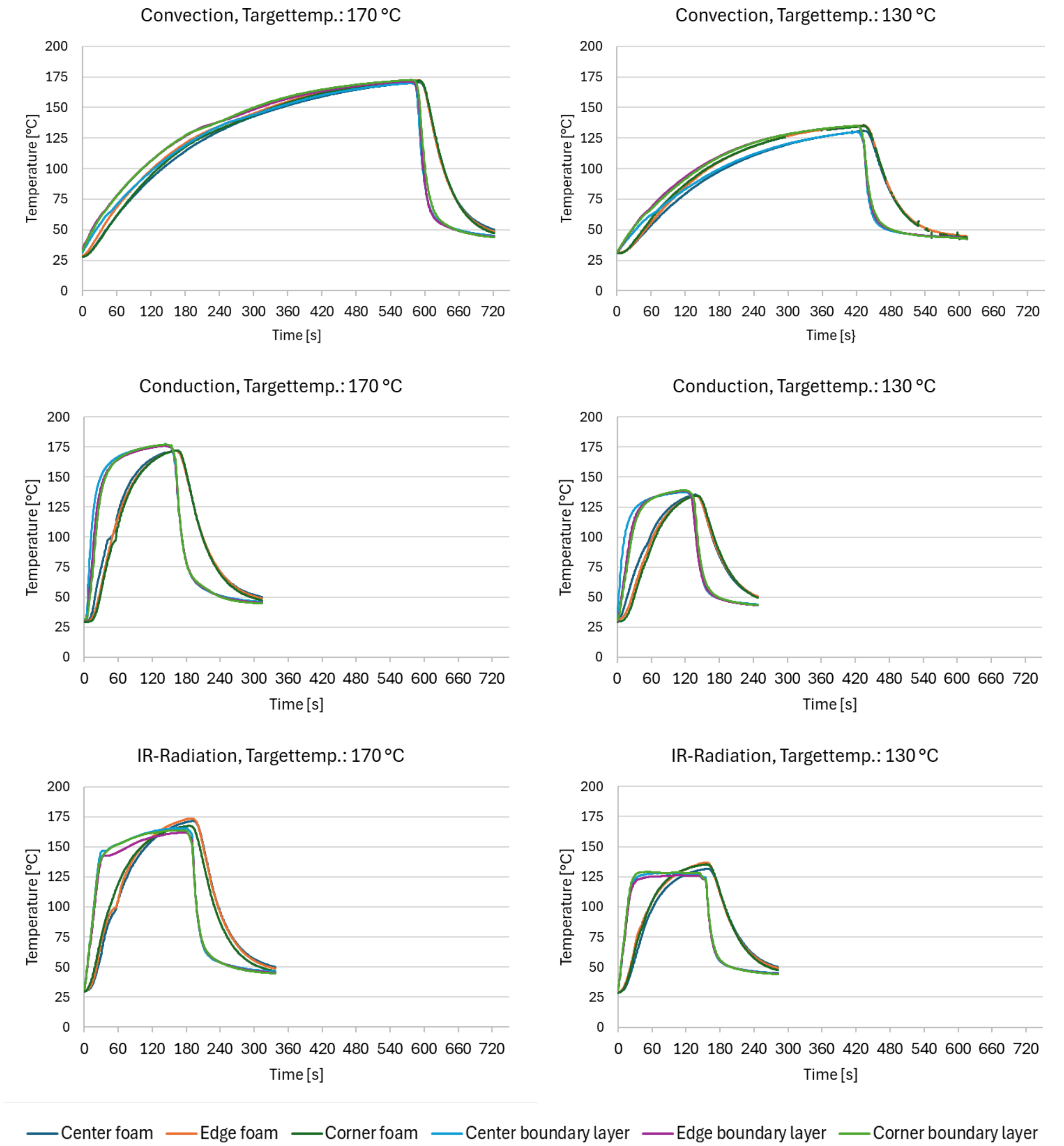

Figure 4 – Temperature profiles

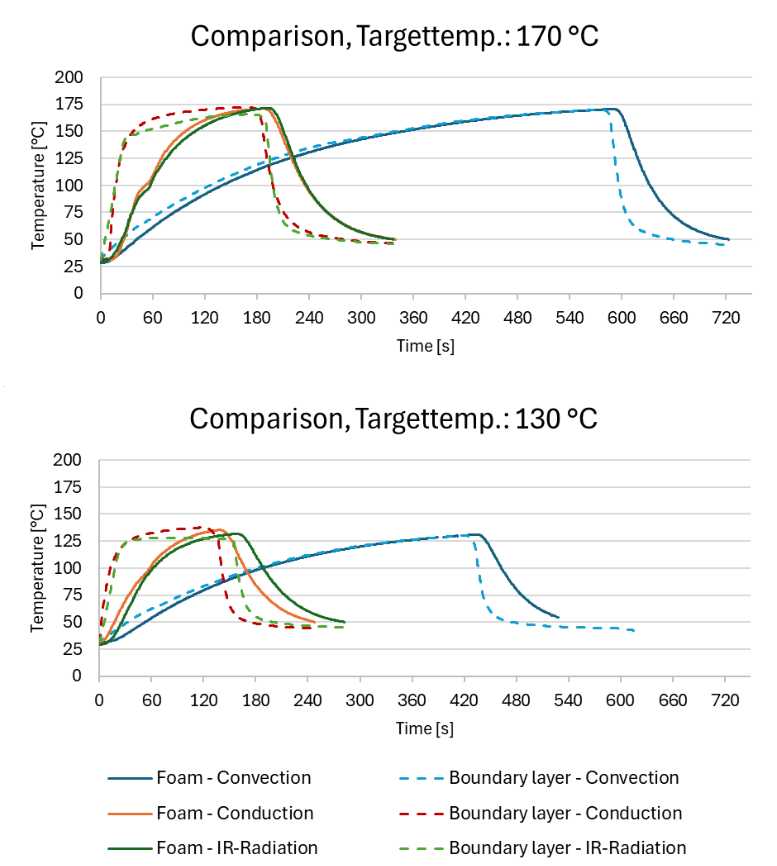

Figure 5 – Comparison of heating-processes at the center position

Table 2 – Heating and cooling times of the compared processes

Target temperature [°C]	Process	Heating times (Mean value) [s]	Standard deviation based on the total heating time-value [%]	Cooling time (Mean value) [s]	Standard deviation based on the total cooling time-value [%]
170	Convection	587.5	2.9	141.6	16.5
	Conduction	108.4	68.3		
	IR-Radiation	131.6	41.7		
130	Convection	406.6	9.1	119.0	6.6
	Conduction	106.7	46.1		
	IR-Radiation	99.8	57.0		

Conclusion

Different pre-heating processes are applied to PET-based mono-material sandwich-structures (facesheets: srPET (Comfil), foam core: T92.100 (Airex)). Convective, conductive and IR-based heating processes show reasonable results, while microwave-based heating was not possible in a sufficient way. However, cycle-times of convective heating are significantly higher than conduction or IR-radiation. Therefore, future studies will focus on the implementation of a pre-heating process aiming for short cycle times while preventing material damage as well as aiming for the transferability to varying sandwich configurations such as color, foam density or semi-finished product thicknesses.

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