THERMOPLASTIC SANDWICH STRUCTURES – PROCESSING APPROACHES TOWARDS AUTOMOTIVE SERIAL PRODUCTION

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ABSTRACT

Sandwich structures can provide a major contribution to weight saving as they exhibit superior stiffness at minimum weight. Using a polymeric foam core offers further advantages: Those materials can lead to elevated energy absorption and thus improve crash properties and at the same time enhance the insulation properties. But at present, there is a lack of established processes enabling the economic production of thermoplastic sandwich structures in industrial scale. Therefore, this work focuses on efficient, process-integrated processing solutions. Two different approaches are discussed enabling the production of thermoplastic sandwich structures with functionalized face sheets at cycle times of app. 2 minutes.

The first approach is based on semi-finished foam cores, which are mostly delivered in the form of plates or sheets. The sheet materials can be thermoformed to curved geometries before applying the face sheets if necessary. Subsequently, endless-fiber-reinforced top layers are fused with the foam core by compression molding. The functionalization of the face sheets has to be locally separated from the foam core in order to avoid damage of the cellular structure.

The second approach is based on bead foam core materials. As the foam is produced by welding of single beads, complex shaped geometries can be realized. In this work, a so called in-situ foaming process is introduced and investigated. The beads are welded between the face sheets of the sandwich and at the same time the core is fused to the thermoplastic matrix of the facings. Compared to normal production of bead foam parts, steaming conditions completely differ, as the steam nozzles are mainly covered by the face sheets. It is demonstrated on lab scale level, that sufficient fusion quality of the beads can be obtained also under these modified conditions and an adhesion quality comparable to pressing processes can be reached.

1 INTRODUCTION

To meet the demands of lightweight structures, composite sandwich structures have been used in aerospace applications for at least five decades [1]. But this design principle also provides numerous advantages for automotive applications: Sandwich structures can offer a major contribution to weight saving as they exhibit superior stiffness at minimum weight. In order to benefit from these advantages possible areas of applications could be roof structures, vehicle floors, engine hoods as well as door panels. The resulting weight reduction leads to a reduction in fuel consumption and thus also in the CO_2 emissions of modern motor vehicles. Regarding electrically driven cars a reduction of body mass is also of major importance as it enables higher driving range.

In addition to the lightweight potential, the good thermal insulation properties of the sandwich foam cores are also beneficial especially for electrical cars as the engine cannot be used any more to heat up the passenger compartment. Thus, the heating or cooling energy saved ultimately results in an increased range.

However, the use of this design principle has not yet been established in automotive serial production. The processes known from aerospace applications are not economically feasible for large series due to their complexity and long cycle times. By contrast to aerospace industry the requirement

specifications of the automotive industry also allow for the use of commodity polymers and technical thermoplastics, which have so far hardly been relevant for sandwich structures.

The usage of thermoplastic materials permits very low cycle times as no curing step is needed. Furthermore, they enable the integration of functional elements such as ribs, inserts or connectors by injection molding or plastic welding in one single process. Another major advantage regarding sustainability is the possibility of re-use of the matrix materials.

But at present there is a lack of established processes enabling the economic production of thermosplastic sandwich structures in industrial scale. Therefore, this work focuses on efficient, highly integrated processing solutions for large volume production of thermoplastic sandwich structures.

2 BACKGROUND

The sandwich concept can be expressed as increasing the bending stiffness of a panel without adding significant weight [2]. The mechanical principle equals a double-T-beam: By separating two stiff face sheets, the bending stiffness increases with rising distance between the sheets as a result of the increased moment of inertia about the beam centroid. In order to keep the face sheets separated and to elevate the total weight of the structure as less as possible the separation is realized by a light core material. Typical core materials are honeycombs, polymer foams or balsa wood. Fig. 1 shows an example of how bending stiffness increases with increasing core thickness and thus distance between sandwich face sheets whereas the total weight only slightly rises. The data corresponds to a sandwich system with foam core (75 kg/m^3) and 2.5 mm thick glass fiber-reinforced epoxy face sheets [2].

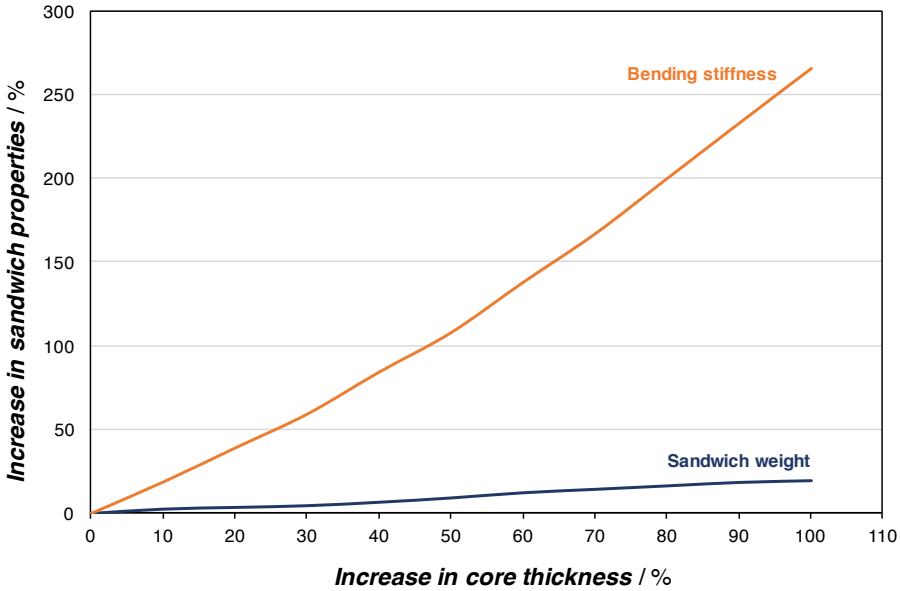

Figure 1: Influence of increasing core thickness on bending stiffness and sandwich weight for a sandwich system with foam core (75 kg/m^3) and 2.5 mm thick glass fiber-reinforced epoxy face sheets acc. to [2].

When a sandwich beam is loaded in flexure, bending loads are carried mainly by the face sheets. Therefore, sandwich skins usually consist of strong and stiff materials. Fiber reinforced composites are very promising candidates to fulfill these requirements.

The main function of the core material is to support the face sheets, prevent their buckling, and keep them fixed in position relative to each other. Thus, the core material has to exhibit sufficient shear and compression properties. Furthermore, the interface strength between the core and the face sheets plays a major role in the performance of a sandwich structure. Thermoplastic sandwich structures allow for the use of the same polymer on the one hand side as matrix material for the fiber reinforced face sheets and on the other hand side also for the foam core. Consequently, those monomaterial structures provide optimum preconditions for high face to core adhesion strength.

A further benefit of polymer foams as core materials is their very low thermal conductivity having values in the order of 10^{-2} to 10^{-3} W/m K, with smaller foam cell size yielding lower values [3]. Furthermore, thermoplastic sandwiches lead to elevated energy absorption and thus improve crash properties.

Besides their properties, sandwich structures based on thermoplastic polymers also provide considerable advantages with regards to processing, compared to previously used thermoset systems. The effective combination of injection molding and welding techniques with pressing processes enables a fully automated production of sandwich structures, while simultaneously integrating functional elements in short cycle times. Thus, the thermoplastic approach offers the potential for economical production of sandwich structures also for large series as relevant for the automotive industry.

3 PROCESSING APPROACHES

For the production of thermoplastic sandwich structures two main processing routes can be distinguished, by the way in which the foam core is brought in between the face sheets. On the one hand side a semi-finished foamed product can be used and thermoformed, if necessary, and subsequently be fused with the stiff outer layers by a pressing process. On the other hand, the foam can be produced in-situ between the face sheets for example by foam injection molding or fusion of foamed beads.

As stated, the first approach is based on semi-finished foam cores, which are mostly delivered in the form of plates or sheets. The sheet materials can be thermoformed to curved geometries before applying the face sheets if necessary. Subsequently, endless-fiber-reinforced top layers are fused with the foam core by compression molding. In the case of compatible core and face sheet materials, an excellent fusion can be achieved at the interface, with no intermediate layers being required as an adhesion promoter. Besides commodity and engineering thermoplastics such as PP and PA, also high-temperature resistant thermoplastic polymers can be processed via this route [4]. But it has to be mentioned, that is processing route allows only limited freedom in part design. For automotive serial production a pre-milling of the foam core in order to realize more complex geometries would not be possible due to additional manufacturing costs and expensive material scrap. Therefore, this approach can mainly be applied to plate-like geometries.

In order to realize geometrically more complex structures, the second approach, the so called "in-situ" production of the foam core is favorable. For this purpose, the pre-formed face sheets are placed in a tool and the foam core is produced directly for example by foam injection molding or welding of foamed beads in-between the face sheets. The production of the core via foam injection molding is particularly suitable for highly stressed components, in which high shear forces have to be transmitted. However, the achievable core thicknesses is limited to app. 8 mm and the minimum achievable densities for polypropylene are at app. 300 kg/m^3, which is already quite low for foam injection molding [5]. But the use of bead foams such as expanded polypropylene (EPP) enables even lower core densities of down to 30 kg/m^3. Besides, also density gradients are also possible through the use of different beads [4]. Bead foams allow for shaping very complex geometries and enable varying core thicknesses between app. 5 mm and several centimeters. In addition, these closed-cell foams also offer superior thermal insulation properties [7].

The integration of functional elements such as rips, facings, clips or other connecting elements in thermoplastic sandwich structures via injection molding reveals additional challenges to the process. During injection molding mold pressures of several hundred up to more than 2,000 bar may occur. This high pressure is necessary to ensure complete filling of the tool cavity and to compensate for the shrinkage of the material during cooling or crystallization. But by contrast, typical foam core materials of sandwich structures only exhibit a compressive modulus at room temperature – depending on material and density – in the range of app. 0.5 to 3 MPa. At higher process temperatures, their stiffness drops significantly. Therefore, a direct impact of high injection pressures on the sandwich core has to be avoided by means of intelligent process or tool design. In the following sections, two possible solutions are presented and discussed.

4 MULTI-STEP PROCESSING: INJECTION AND COMPRESSION MOLDING

The foam core can be prevented from the injection pressure by locally separating the functionnalization of the face-sheets employing a multi-stage process: This approach is characterized by a preliminary production of one or two outer layers with corresponding functional integration and subsequent joining of functionalized face sheets in a separate tooling as illustrated in Fig. 2. This processing sequence also enables the parallelization of the single steps and thus reducing cycle time. The handling between the necessary machinery can be carried out fully automatically.

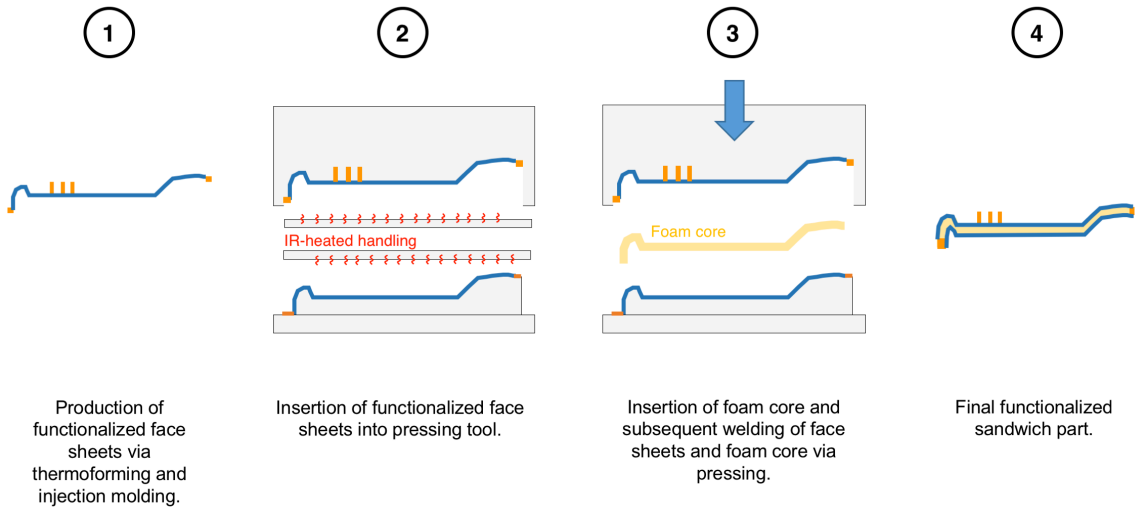

Figure 2: Schematic process description for multi-step production of thermoplastic sandwich structures: The functionalization of the face sheets is locally separated from fusing face sheets and core.

Organosheets based on woven fabrics can be used for the manufacturing of continuous fiber reinforced face sheets. The organosheets need to be cut to the required contour, followed by heating, forming and overmolding [8]. Alternatively, unidirectional fiber-reinforced tapes, so-called UD tapes enable to orient the fibers in any desired load direction, allowing to manufacture load-specific components at a minimum scrap rate [9]. Novel preforming techniques for thermoplastic UD tapes reach cycle times to work in-line with the injection molding step. Processes like FORCE [10], developed by Neue Materialien Bayreuth GmbH, enable a fully automated production of functionalized composites which can be employed as face sheet structures. The functionalization via injection molding also opens the possibility for integration of metallic inserts or electronic components.

Finally, with the multi-stage production cycle times in the range 1.5 to 2 minutes for the manufacture of highly integrated sandwich structures can be realized.

5 IN-SITU FOAMING OF BEAD FOAM CORES

One of the essential advantages of the bead foam technology is the possibility of producing complex, three-dimensional, net-shaped light-weight foamed parts at densities down to 30 kg/m^3. For the foaming process the expanded polymer beads are filled via injectors into the tool cavity using compressed air. Afterwards a static pressure of approximately 1.5 to 4 bar is applied in order to compress the beads and ensure a complete filling of the cavity. Following, the cavity is ventilated with hot steam. During steaming, the beads form physical links due to inter-diffusion of chains of neighbouring beads [11].

The steaming process itself consists of three steps: At first, the air between the beads is purged out and the mold is pre-heated. During this step, steam is flowing parallel to the mold with all the valves open. In the second step, the steam flows through the mold, which is called cross steaming. During this step, the steam supply and exit valves opposite to each other are open. Finally, steam is guided into the steam chamber while the exit valves are closed to improve surface quality by the creation of a

skin – this last step is called autoclave steaming [12]. A cooling system inside the tool accelerates the stabilization of the foam and enables ejection of the part after a total cycle time of app. 60 to 120 s, mainly influenced by part thickness.

For the in-situ production of thermoplastic sandwich structures with bead foam cores the face sheets are prepared as described in the section above via thermoforming and injection molding. Subsequently, the functionalized facings are placed on both tool surfaces of the foaming mold as shown in Fig. 3. Following the beads are filled in between the face sheets. But due to the placement of the top layers directly onto the mold surface the steam inlets are mainly covered. Steam can only penetrate in between the beads from the narrow sides of the cavity – as also illustrated in Fig. 3 – if no notches are in the face sheets.

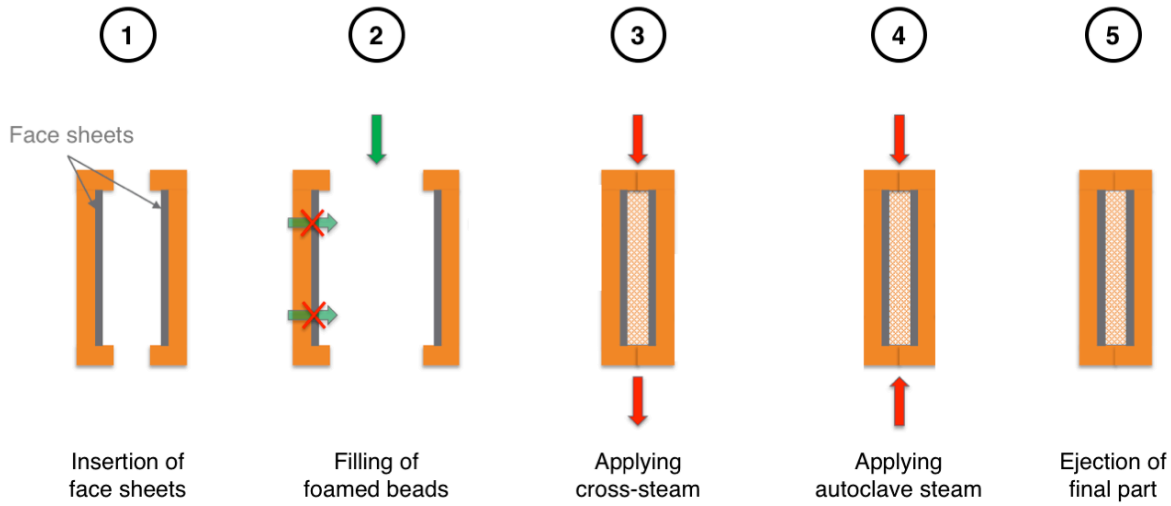

Figure 3: Processing sequence for in-situ production of thermoplastic sandwich structures with bead foam core.

Therefore, for the in-situ production of thermoplastic sandwich structures it is necessary to gain knowledge about the fusion quality of the bead foam core under the modified steaming conditions. It has to be evaluated whether the foam quality significantly varies along the extended steam path.

5.1 Welding behavior of bead foam core

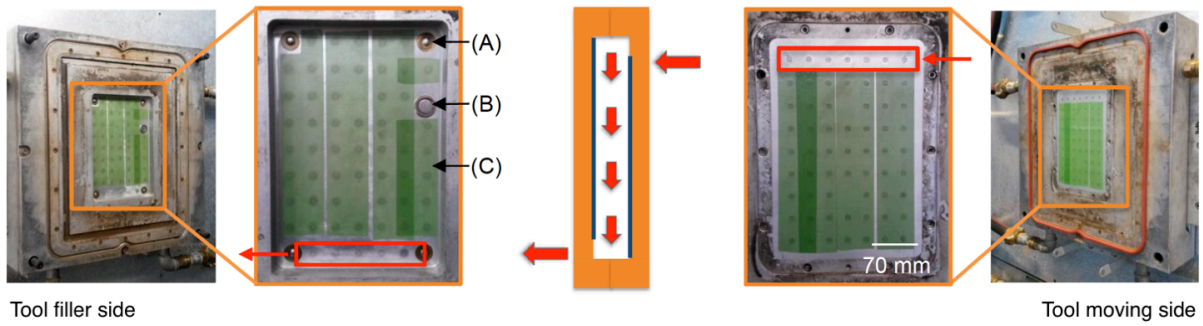

Figure 4: Trial setup: Steam nozzles are covered by polyester tape. Cross-steaming is only possible from top on tool moving side to bottom on tool filler side.
(A) Active fillers; (B) Pressure sensor; (C) Covered nozzles.

In order to characterize the influence of the different steaming conditions on the welding quality of the foam core, the steam nozzles in a plate mold (200 x 300 mm^2) were sealed with polyester tape. Only the steam nozzles in the area of the steam inlet in the upper area as well as the steam outlet in the lower area were not covered as shown in Fig. 4. Cross-steaming was carried out from top to bottom of the mold employing a steam pressure of 3.8 bar. In this trials no autoclave steaming has been done, as

the cross-steaming dominates the bead fusion process. Expanded polypropylene beads Neopolen P 9230 K having a bulk density of 20 to 30 g/l supplied by BASF SE (Ludwigshafen, Germany) were utilized as core material. For all trials a modified TransTec 72/52 steam chest molding machine (Teubert Maschinenbau GmbH, Blumberg, Germany) has been used.

Plates with a thickness of 22 and 32 mm were molded with varying cross-steaming time (5 s and 25 s). After an optical inspection, the density of the plates has been measured next to the steam inlet and in the area, which has been next to the steam outlet during molding. The results summarized in Fig. 5 show that there is a slight rise in density between steam inlet and outlet. The density in the vicinity of the steam outlet is app. 4 to 8 % higher compared to the region around the inlet. A correlation with steaming time or plate thickness cannot be drawn.

The following reasons can be responsible for the difference in density: As filling has also been carried out from top to bottom of the cavity using only the upper injectors, the heavier particles settle down, whereas the lighter beads are carried by the turbulent air flow and stay in the upper region of the mold. Furthermore, entrapped air between the beads cannot escape especially in the upper region of the mold when applying a static compaction pressure as the steam nozzles are sealed. Additionally, during the following cross-steaming the hot steam condensates when reaching the colder beads in the upper region of the cavity. Even though the beads and the mold have been heated up as described above, there is a difference in temperature between the steam and the bead surface as the foamed particles thermally insulate their selves very well from the tool cavity. In the upper region the condensate cannot leave the tool, as the whole surface is closed. This fact has been proven by changing the direction of steam flow. When the cross-steam is applied from bottom to top, imperfections caused by condensate can be found in the bottom region – thus, also near the steam inlet.

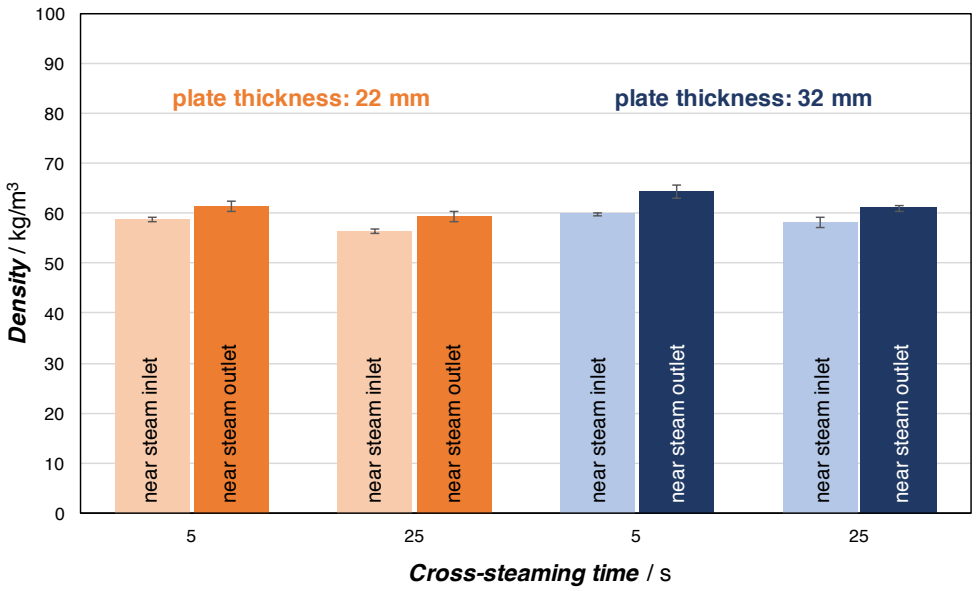

Figure 5: Influence of cross-steaming time, specimen position and plate thickness on density of welded plates.

The welding quality of the fused foam has been quantitavely characterized by tensile tests. From each plate one specimen has been cut out next to the steam inlet and another one in the vicinity of the steam outlet using waterjet cutting. The foam skin has been removed with a band saw. The tensile tests have been carried out according to DIN 53430 employing a Zwick Z020 universal testing machine (Zwick GmbH & Co. KG, Ulm, Germany). Before testing, all specimens were preconditioned at standard climate. Five valid tensile specimens were used for the statistical evaluation.

The resulst of the tensile tests are shown in Fig. 6. It can be observed, that steaming time has no impact on the fusion quality within the investigated range. Already after 5 seconds of cross-steaming a sufficient welding is reached. Furthermore, also the plate thickness doesn't reveal a major influence.

But it can be recognized, that tensile strength is 5.5 to 8.5 % higher near to the steam outlet, compared to the region around steam inlet. This can be adressed to the reasons already described above regarding the differnces in density. Especially the condensation of the steam might affect the fusion quality.

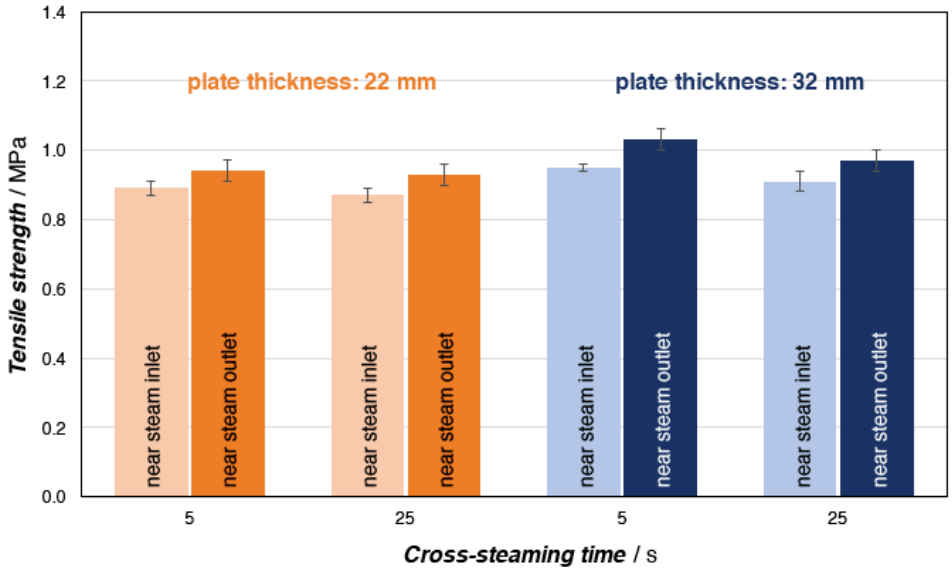

Figure 6: Fusion Quality: Influence of cross-steaming time, specimen position and plate thickness on tensile strength of bead foams.

5.2 Face to core adhesion

In the next step, glass fibre reinforced face sheets with a polypropylene matrix were attached to the tool surface in order to directly fuse the beads between the sandwich surface layers and weld the EPP foam core to the thermoplastic matrix of the facings at the same time.

The face sheets consist of a $[0/90]_2$ orthotropic layup based on unidirectionally glass fiber reinforced (60 wt-%) tapes type Plytron GN638T delivered by Elekon AG (Luzern, Switzerland). The consolidation of the tape stack has been done in a double belt press.

For the in-situ production of the bead foam core, the welding of the beads has been carried out employing a cross-steaming time of 25 s. Subsequently an autoclave steaming also at a steam pressure of 3.8 bar has been applied in order to ensure a good fusion between face sheets and core. Autoclave steaming time has been varied between 0 and 30 s.

The adhesion quality between face sheets and bead foam core was characterized by flatwise tensile tests according to DIN EN ISO 4624 employing a Zwick Z1485 universal testing machine (Zwick GmbH & Co. KG, Ulm, Germany) with a 10 kN load cell. In order to ensure proper adhesion of the testing specimens to the test metal fixture blocks, the sandwich facings were roughened with abrasive paper of 180 grains. The surfaces of the fixture blocks as well as of the sandwich specimens were cleaned with isopropanol before attaching the blocks to the specimen surface employing WEICON Easy-Mix PE-PP 45 construction adhesive (WEICON GmbH & Co.KG, Muenster, Germany). The adhesive has been cured for one day at standard climate.

The results obtained are shown in Fig. 7. It can be observed, that face to core adhesion improves with increasing autoclave steaming time. It has been expected before, that the autoclave steaming dominates the fusion quality between the polypropylene-based face sheets and the EPP foam core. An autoclave steaming of 30 s leads to a comparable interface strength as could be reached in previous work [13] for welding the same face sheets to an EPP foam core via pressing.

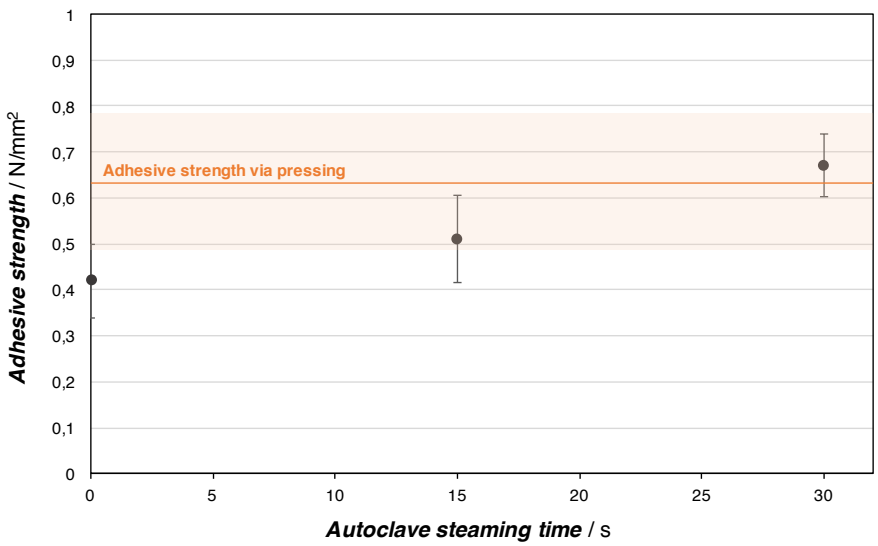

Figure 7: Influence of autoclave steaming time on face sheet to EPP-core adhesion. The orange line indicates the benchmark based on fusion of face sheets and core by pressing. The light orange area represents the range of deviation for the benchmark.

6 CONCLUSION AND OUTLOOK

In this work two processing approaches for the production of thermoplastic sandwich structures, meeting cycle time requirements for large volume serial production, have been discussed. They can be distinguished by the way in which the foam core is brought in between the functionalized face sheets. On the one hand side pressing can be used to fuse the previously prepared facings to semi-finished foam cores. On the other hand, the foam core can be produced in-situ between the (functionalized) face-sheets. Furthermore, it has been emphasized, that the functionalization of face sheets via injection molding has to be locally separated from the foam core in order to avoid damage of the core due to the high injection pressure.

Special attention has been drawn to the in-situ production of bead foam cores. Compared to normal production of bead foam parts, steaming conditions completely differ, as the steam nozzles are mainly covered by the face sheets. It is demonstrated on lab scale level, that sufficient fusion quality of the beads can be obtained also under these modified conditions. It has to be taken care, that the beads are preheated properly before welding in order to avoid high amounts of condensate, which cannot escape from the core. Furthermore, it is shown, that the fusion quality between face sheets improves with increasing autoclave steaming time.

In future work, this results have to be transferred to larger and geometrically more complex structures in order to identify maximum length of steam path, that still provide sufficient fusion. Besides, the ultimate reachable interface strength has to be determined by further extending autoclave steaming. Finally, also other foam densities and material combinations have to be considered in ongoing work.

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