

Fully thermoplastic honeycomb sandwich composites produced by fusion bonding

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Statements and declarations

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Abstract

A new method is proposed to create fully thermoplastic sandwich panels by fusing a cellular Polyetherimide (PEI) core with a polyaryletherketone (PAEK) facing through infrared heating of the skin followed by rapid pressing. The process eliminates the need for adhesives, reducing weight and cycle times while enhancing recyclability.

The effects of processing temperature on core erosion, skin-core adhesion, and crystallinity of the PAEK matrix were investigated. Results show that higher temperatures lead to increased core erosion but also improve skin-core adhesion up to a certain point. The optimal processing temperature range was found to be around 310-320°C, where a balance between minimal core erosion and maximal adhesion strength is achieved. Flatwise tensile testing demonstrated that samples processed at 310-320°C exhibit both adhesive and core tensile failure modes, with higher strengths achieved at these temperatures. The method requires optimal tuning of the processing parameters and core geometry to achieve reliable and strong bonds between the core and skin.

This research contributes to the development of sustainable manufacturing methods for thermoplastic sandwich structures, offering potential applications in aerospace and other industries where lightweight, high-performance materials are critical. Future work will focus on scaling up this technology and exploring its applicability to more complex geometries and material combinations.

Keywords: thermoplastic sandwich, thermoplastic composite, welding, hot press forming, recycling

Introduction

Sandwich structures have played an integral role in both aviation and spaceflight ever since their introduction to aircraft in the 1930s, mainly for their high flexural stiffness at low weight. They consist of two thin outer layers with high in-plane strength and stiffness and a low-density core providing high compressive and shear strength (1). The aerospace industry uses a number of various core and skin materials today. Cores typically consist of a polymer foam or come in the shape of a honeycomb made of aramid paper or sheet aluminium. Honeycomb or lattice cores are preferred due to their higher properties compared to stochastic architectures such as foams. Thermoplastic honeycombs, typically made of Polyetherimide (PEI), have found sparse application in interior panels in aircraft (2). The skins are typically made up of a high-performance thermoset composite which is adhesively bonded to the core material.

Thermoplastic composites are gradually finding more implementation in the aerospace industry. Their formability makes them an attractive alternative to fibre reinforced thermosets in clips and brackets. Being weldable, they are used in components where the use of fasteners is undesirable or impractical. While they have yet to be applied in flight critical components, the industry is making large investments to achieve thermoplastic primary structures, as evident by the completion of the multifunctional fuselage demonstrator, a full scale model of a thermoplastic fuselage section showcasing the state of the art of numerous manufacturing and joining techniques. The thermoplastic composite materials envisioned for this transition almost exclusively use polymer matrices from the Polyaryletherketone (PAEK) family, offering high mechanical properties as well as thermal, chemical and creep resistance.

While sandwich panels offer some unique properties, the aviation industry is trying to find alternatives, as they are labour intensive in their manufacture, inspection and maintenance (1), (3). A thermoplastic sandwich panel produced through fusion between core and facing eliminates the need for an adhesive, reducing the complexity of the part. Such a material would be easier to disassemble or repair and could be joined or locally reinforced using welding rather than mechanical fastening (4). The panels as a whole could also be thermoformed, allowing for the manufacture of more complex structures. The absence of a thermoset bond layer greatly enhances recyclability for end-of-life components, notably if core and facing are made from the same resin. As no curing is required, the manufacturing time is drastically reduced.

Thermoplastic sandwich panels with foam cores have been produced in a number of ways, one notable example being in situ foaming, where the core is produced from PEI films and a blowing agent lodged in between the finished PEI composite skins inside a press (5). Despite being cheaper to produce than conventional options, these structures have not seen large scale implementation in aircraft, largely due to poorer properties due to the foam core and limitations in the maximum thickness. Honeycomb cores offer better properties but cannot be formed in situ and require novel manufacturing approaches to bond them to the skins by fusion (6).

Composite welding techniques, notably induction, resistance and ultrasonic welding are designed to apply local heating to the bond region and have been successfully applied in thermoplastic sandwich bonding. Martin et al. (7), (8) have used induction welding to fusion bond small sections of additively manufactured PEI honeycomb to a PEEK facing with a PEI interlayer and achieved cohesive failure of the honeycomb under tension. Zhang et al. (9) achieved good interfacial adhesion for their resistance welded thermoplastic corrugated core sandwich construction and Oliveira et al. (10) used ultrasonic spot welding to bond a skin to a thermoplastic core.

The successful application of a number of composite welding techniques shows them to be highly suited to bonding thermoplastic sandwich and have the potential to give rise to a vast design space, where sandwich structures can be manufactured in situ and structures can be locally reinforced or repaired after installation. However, evenly welding large or curved surfaces remains a massive challenge (11), (12) and the studies mentioned prove their concepts on specimen level only. Grünewald et al. (13), (14) used a different approach, where the skins were heated in an oven before being transferred to the core and put under pressure. This method appears more suited for larger components with some curvature but has so far only been proven using a foam core.

Table 1: Thermal properties of resins evaluated for the process (15)

Polymer	Glass Transition Temperature	Melting Point	Typical Processing Temperature
LM-PAEK	147°C	305°C	340–385°C
PEEK	143°C	343°C	370–400°C
PEI	217°C	-	320–350°C

The present study proposes a new method to create fully thermoplastic sandwich panels by fusing a cellular PEI core with a PAEK facing through infrared heating of the skin and rapid pressing. The process eliminates the need for adhesives, reducing weight and cycle times while enhancing recyclability. The effects of processing temperature on skin-core adhesion and core erosion are investigated by flatwise tensile testing and cross section microscopy.

Methodology

Materials and manufacturing

PEI 144 kg/m³ tubular honeycomb from Tubus Bauer (Bad Säckingen, Germany) was selected to function as core material. It was chosen over a corrugated hexagonal honeycomb produced by EconCore (Leuven, Belgium) due to its higher compressive properties. The face sheets were supplied by Toray (Nijverdal, Netherlands) in the form of a 4 ply [0/90, ±45]_s consolidated laminate using their T300JB carbon woven prepreg. The first configuration used a Low-Melt-Polyaryletherketone (LM-PAEK) facing matrix and the second one used a Polyetheretherketone (PEEK) matrix. The initial laminate thickness was 1.24 mm. A layer of Sabic (Bergen op Zoom, Netherlands) Ultem 1000B PEI was then co-consolidated onto one side of the laminates to function as a bond surface between the PEI core and the face sheets. The LM-PAEK matrix laminates used a 50µm thick layer while the PEEK matrix laminates compared 50 µm, 100 µm and 150 µm layer thicknesses made by co-consolidating one, two, and three PEI layers, respectively. An LM-PAEK laminate was left without interlayer to function as reference. An overview of the used laminates is shown in Table 2.

Obtaining adequate fusion bonding between a thermoplastic core and face sheet requires some melting of the polymer in both constituents as well as pressure to consolidate the bond. Due to the delicate nature of the core material, limitations apply in both the application of heat and pressure. Fusion requires exposure of the bond surface to temperatures well beyond the glass transition temperature (T_g) of PEI (see Table 1). The core as a whole may not exceed this temperature as virtually all structural integrity is lost at this point leading to core crushing. Therefore, the interface region needs to be subjected to localised heating, application of pressure and then rapid cooling to avoid gradual erosion of the core. The semi-crystalline PAEK matrix materials used in the face sheet remain structurally intact well beyond their T_g. Nevertheless they cannot be heated beyond their melting point as the subsequent consolidation on the uneven core surface would cause undulation and possible deconsolidation. A co-consolidated PEI interlayer on the skin is used to create the bond with the core without requiring the composite matrix to melt. PEI diffuses well into PAEK materials, forming a strong bond between core and face sheet (16).

Table 2: Overview of material and process combinations

Reinforcement	Matrix	Joining Method	Interlayer	Nominal thickness	Facing Temperature
5 Harness Satin T300JB Carbon Woven Prepreg	LM-PAEK	Adhesive	PEI 50 µm	1.24 mm	-
	LM-PAEK	Fusion Bonding inside Press	-	1.24 mm	290°C
			PEI 50 µm	1.29 mm	290°C
	PEEK		PEI 50 µm	1.29 mm	340°C, 350°C
			PEI 100 µm	1.34 mm	310°C, 350°C
			PEI 150 µm	1.39 mm	300°C, 320°C

Three trial runs were conducted in total. In the first one, the general feasibility of the process was tested. The later ones aimed at iteratively improving core - face sheet adhesion. After the first trial, LM-PAEK was deemed less suitable as a matrix material due to its lower melting point

and abandoned. Nevertheless, the initial obtained results are presented here as they help improve the understanding of the process as a whole.

For reference, a sandwich panel was produced with adhesively bonded core and facings. It used the same Tubus Bauer PEI core as the fusion bonded configurations and LM-PAEK face sheets with 50 μm PEI interlayer. The core was placed between the two laminate sections with a layer of Hexcel Hexbond 322 film adhesive placed on the interface. The stack was covered with a vacuum bag and autoclave consolidated for 1 h at 175°C and 3 bars.

Before the press operations, the laminate sections were dried in a Nabertherm NA DB200 forced convection oven to mitigate later deconsolidation due to devolatilization. Slange et al. observed the escape of volatiles in PEEK laminates up to 250°C and determined 3h at this temperature as an optimal drying cycle (17). However, exceeding T_g of the PEI interlayer was observed to cause changes to its appearance. Therefore, lower temperatures were used. In the first two trials, blanks were dried at 150°C for 4 h. For the ultimate trial, the temperature was increased to 210°C at the same duration.

Skin core joining

The method proposed to fuse core and face sheet makes use of the stamp forming setup present at the research facility. It consists of a Wickert WKP 1000 S press, an infrared (IR) oven and a Kuka robotic arm to transport the face sheet from the oven to the press at high speed. A modular frame was used to fixate the blank. Two 190x190 mm wide steel blocks mounted to the upper and the lower press plates functioned as tooling.

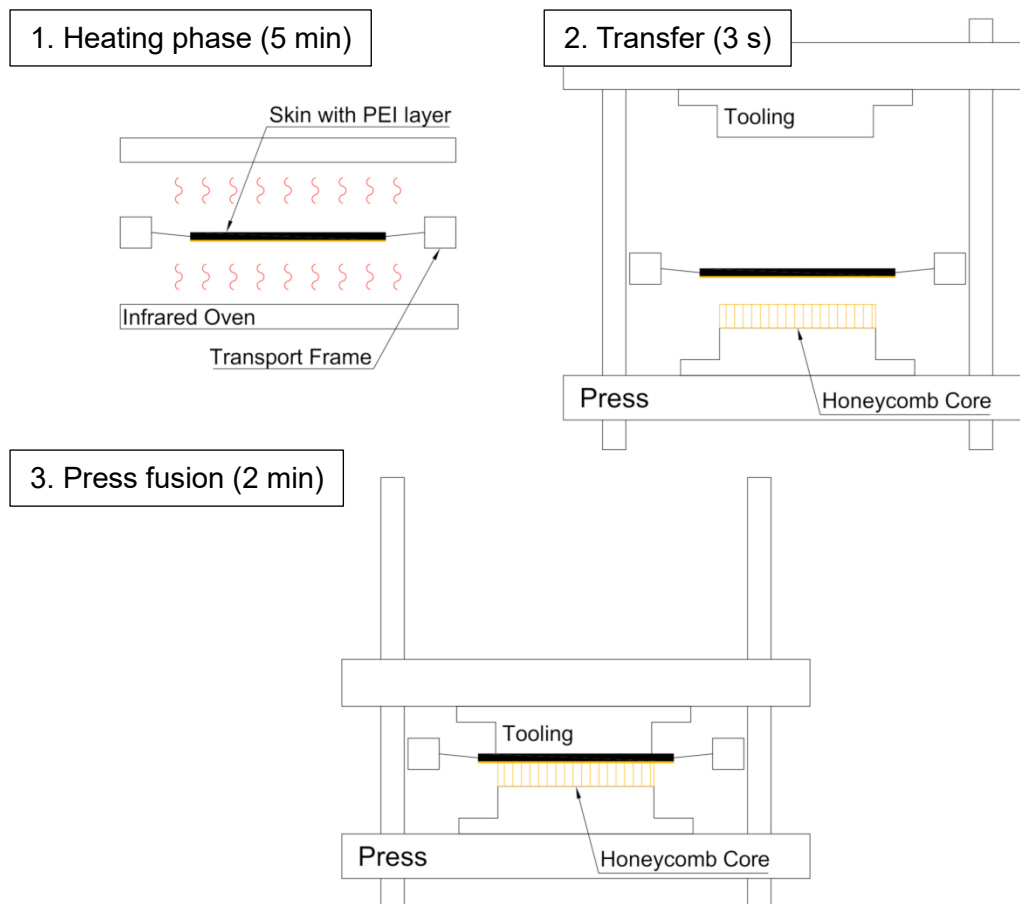


Figure 1: Schematic representation of manufacturing process

The core was placed on the lower block, while the upper block was used to press the hot laminate onto the core after it was heated and transferred into the press. The face sheet dimensions were 220x190 mm to provide some excess for gripping. The setup is shown in Figure 1. During initial trials, a thermal imaging camera was placed in the press cell to measure the blank temperature just before press closure. The blank was gripped at its four corners using 5N paper clips (see Figure 2). Two thermocouples were attached to the lower face of the laminate at opposing edges to measure the temperature during heating in the IR oven.

During initial trials, a movable infrared heater panel was placed over the core to heat the core surface to 200°C prior to fusion. This method however was abandoned as evaluation of the thermal imaging revealed that the temperature dropped to almost ambient temperature immediately after the heater was removed. Trials with a heated tooling were also abandoned as temperatures in excess of 150°C resulted in a large part of the core being crushed.

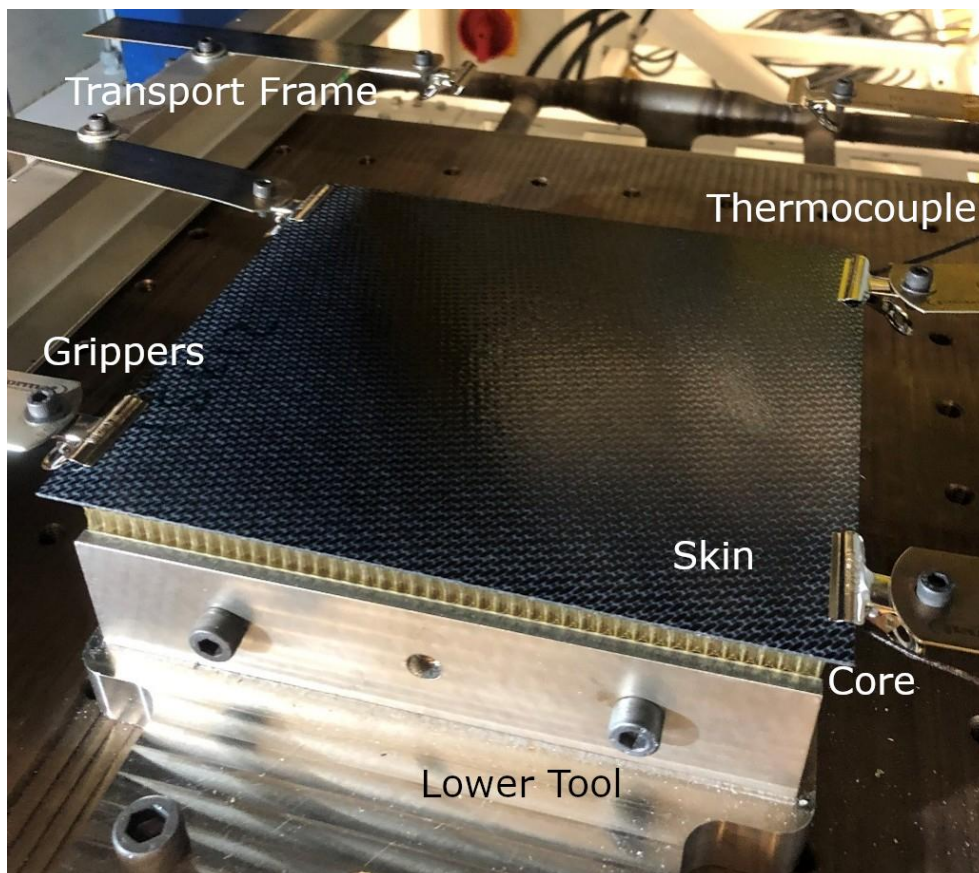


Figure 2: Face sheet and core during alignment in the press cell

At the start of a press cycle, a honeycomb section was placed on the bottom tooling. Then the transport frame was moved into the press and the blank installed in the grippers with the co-consolidated PEI layer facing the core, as shown in Figure 2. This position was calibrated to slightly press the face sheet onto the honeycomb. Before moving the blank into the oven, the thermocouples were installed in the front left and rear right grippers with the tip bent upwards to push into the laminate.

In the IR oven, the blank was heated to the target temperature with the IR heaters set to 100°C above the target. If a temperature delta was observed between the two thermocouples, the mean would be taken as the control value. Heating times were between 5 and 8 minutes, depending on the target temperature. After it was reached, the blank was positioned on the core

and the press closed. The time from the oven to full closure of the press was about 3s. The pressure was set at 8 bar during initial runs and later increased to 10 bar with a 2s pressure build-up. Pressing time was 60s in the first runs and later set to 120s to make sure the specimen had cooled completely.

After opening of the press, the transport frame containing the product was moved out of the setup, where the specimen could be carefully removed from the grippers. To produce a double sided sandwich panel, the one-sided panel produced in a previous run was placed back on the tool with the core facing upwards and the process could be repeated. Single sided sandwich specimens were used to determine the flatwise tensile strength.

Material characterisation

After manufacturing the sandwich panels, their thickness was measured to determine the level of core erosion. Images were taken of the skin surface to document discolorations. After this, samples were extracted for optical microscopy, differential scanning calorimetry (DSC) and flatwise tensile testing. Care was taken to extract the specimens from the centre in order to avoid the possible zones of poor adhesion at the edges.

Flatwise tensile testing was carried out to evaluate the quality of the interface according to the ASTM C297 standard (18) in a 100 kN Instron test bench. Exclusively, one sided sandwich configurations were used similar to the one shown in Figure 3, with the bare core side attached directly to the tab. Each test set used 5 samples from the same panel with a 6th one as reserve.

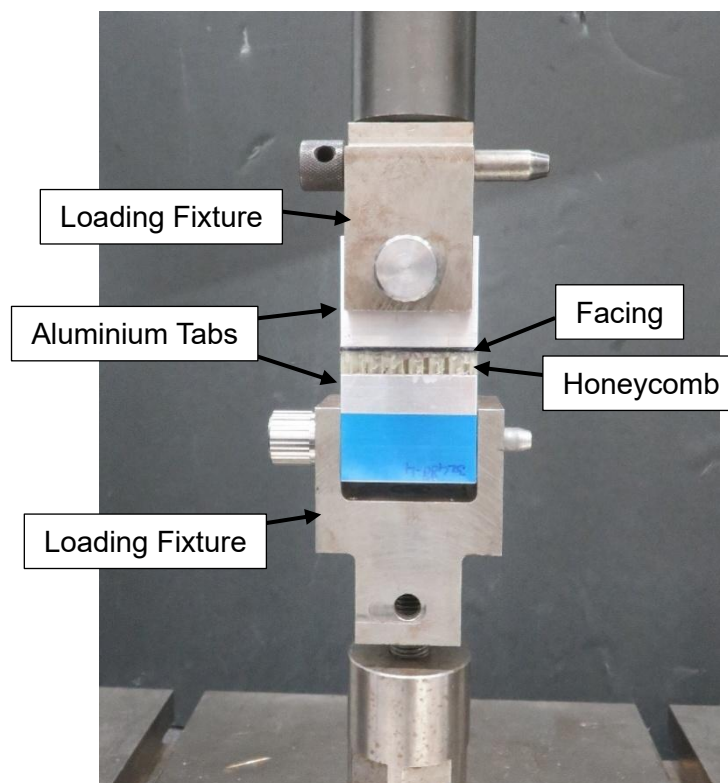


Figure 3: Flatwise tensile testing setup in the Instron test bench

The 50x50 mm specimens were cut out using a diamond grinding disc. The thickness of the samples was recorded after cutting, while the width measurement required to calculate flatwise tensile stress would be taken just before testing. The bonding surfaces on the aluminium tabs, as well as the sandwich face sheet were grit blasted, cleaned and then glued

using Scotch Weld EC-9323 B/A adhesive in the configuration shown in Figure 3. The test samples were placed in the bench and loaded at a rate of 0.25 mm/min until fracture occurred. The fracture surface was examined visually for the failure behaviour.

Flatwise tensile testing knows four different failure modes: Skin failure, core failure, adhesive failure of the adhesive and cohesive failure of the adhesive. Skin failure occurs, generally in the form of delamination, when the core and interface are stronger than the skin in the out-of-plane direction. Core failure occurs when the core tensile strength is exceeded. Adhesive failure occurs on the interface between core and laminate and is adhesive in nature if the adhesive remains on one of the substrates in its entirety. Cohesive failure on the other hand is characterised by structural failure within the adhesive itself. As the welded interface seen in the present sandwich panels does not contain a separate adhesive phase, the definitions of adhesive failure and cohesive failure need to be interpreted in a slightly different way. Adhesive failure is defined as the case where the core and skin are separated cleanly with no residue remaining on either of the substrates. Cohesive failure is said to occur if the fracture clearly involves the interface but parts of either the core or the skin remain on the other substrate.

Optical cross section microscopy was conducted to study the interface, as well as to identify potential damage to core and face sheet. A 20x10 mm sample was cut from each panel configuration using a diamond grinding disc, embedded in a dedicated resin and the surface ground and polished. A fast curing resin was used to prevent penetration of the monomers into the PEI sections of the sample.

DSC was carried to evaluate the crystallinity of the PAEK skins after processing the sandwich panels. A 5 mm wide circular disc was cut from the centre section of the skin and then delaminated. Only the upper part was evaluated to avoid traces of the PEI from the bottom. The sample was heated to 400°C at 10°C/min.

Results and Discussion

Optical Microscopy

The cross section microscopy images (see Figure 4) show a section of the face sheet as well as the connection to the core below. The vertical columns represent the cross sections of the tube wall. Their thickness and spacing differ due to the sections being taken at different locations in the sandwich panel. The images show the varying degrees of core erosion, depending on the skin temperature. At 300°C, only minor core deformation was observed (see Figure 4 A), with the severity increasing with temperature. The 310°C and 320°C samples shown in Figure 4 B and C achieved the highest bond strength (see

Flatwise Tensile Testing). The deformation pattern continuously followed the same principle, where the cylinder walls of the core would fray inwards under pressure from the facing. At higher temperatures, cracks were observed between adjacent cylinder walls, as seen most prominently in Figure 4 D.

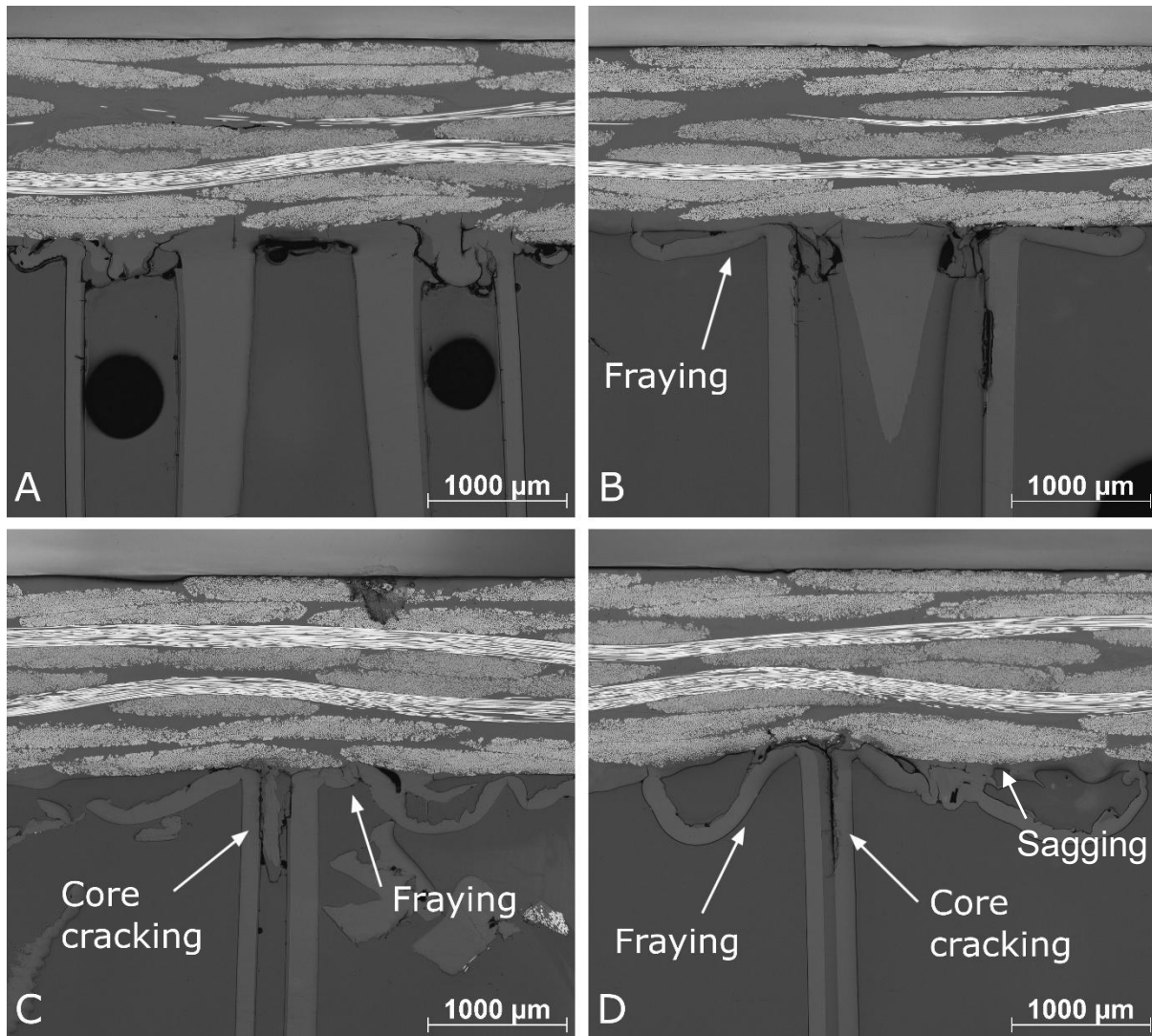


Figure 4: Optical cross section micrographs of variously processed fusion bonded PEEK sandwich panels:

- A:** PEEK face sheet dried at 210°C and pressed at 300°C, 150 μm PEI interlayer
- B:** PEEK face sheet dried at 210°C and pressed at 310°C, 100 μm PEI interlayer
- C:** PEEK face sheet dried at 210°C and pressed at 320°C, 150 μm PEI interlayer
- D:** PEEK face sheet dried at 210°C and pressed at 350°C, 100 μm PEI interlayer

For the present configuration, core erosion was found to follow a distinctive pattern. The residual temperature in the facing causes local softening of the cylinder walls, resulting in them deforming inwards under compression. The deformation then leads to exposure of a new, lower section of the cylinder to the hot facing, causing it to also deform inwards. The process continues until the temperature in the facing drops below a threshold where it is able to sufficiently soften the PEI and the core is able to resist the compressive force. As seen in Figure 4 D, the frayed cylinder edges disconnect from the facing after being pushed inwards. Good contact between core and face sheet appears to occur only directly above the intact cylinder wall, which is the section deformed towards the end of the process. This explains why higher temperatures do not result in better core-facing adhesion, as the sections of the cylinder which

are crushed initially and under higher temperature ultimately do not make contact with the facing and therefore do not contribute to the bond. Changing the geometry of the core could improve this behaviour, possibly by using a different honeycomb, such as a hexagonal configuration. Alternatively, the contact area could be optimised for adherence, for instance by filleting the ends of the tubes though contact with a hot plate. The temperature dependency of core erosion is visualised in Figure 5, showing the decrease in panel thickness with higher processing temperatures.

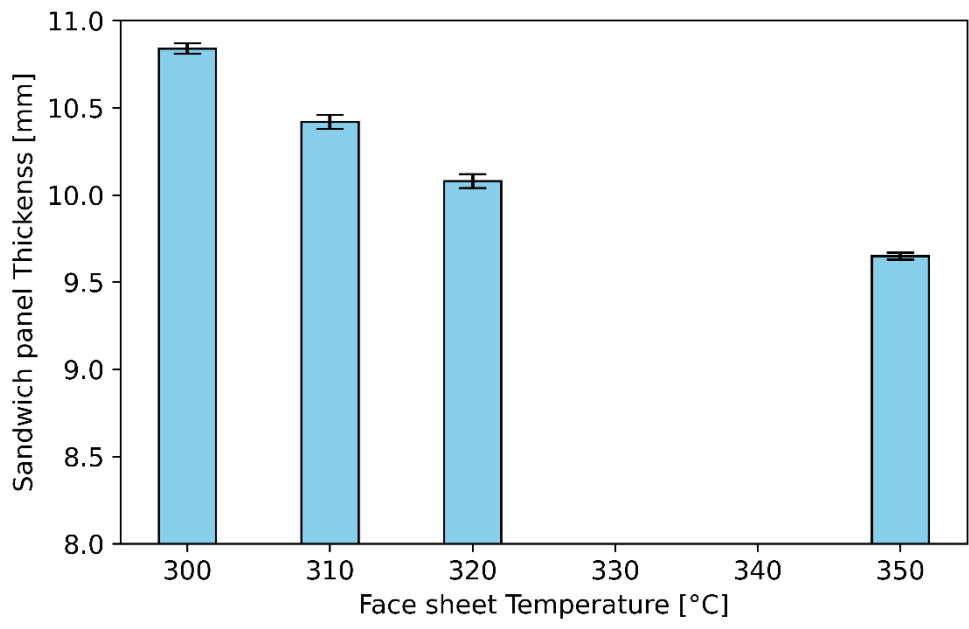


Figure 5: Sandwich panel thickness (PEEK facing, single sided configuration) depending on the facing temperature

When approaching the melting point of the resin system, the facings exhibited sagging. Sagging was initiated in LM-PAEK panels at around 300°C and at 340°C in PEEK panels. Pressing the facings in the molten state then caused waviness in the skin through bulging between the core cylinder walls, as can be seen in Figure 4 D. The phenomenon is thought to be generally beneficial to core-facing adhesion due to better mixing of the resins, as well as the tubes being pushed into the laminate. However, due to the cylinders deforming in the fraying mode rather than pushing into the skin, this occurred only to a very limited extent. Furthermore, waviness is considered a defect which decreases the properties of the laminate and is somewhat unpredictable. Melting of the facing was then taken to be an upper limit to the processing window.

Laminate defects occurred in the form of voids, which were present in all facings dried at a too low temperature. Figure 6 depicts an LM-PAEK facing which was dried at 150°C and heated to 290°C, below the melting point of the material. Note the severe laminate defects in the form of deconsolidation and surface irregularities. These do not occur in the facings dried at 210°C shown in Figure 4, even when heated to beyond their melting point. Considering the findings of Slange et al. (17), deconsolidation is a result of volatiles remaining in the laminate during drying which evaporate violently at higher temperatures. Despite the authors suggesting drying at 250°C, 210°C was found to be sufficient in avoiding void formation.

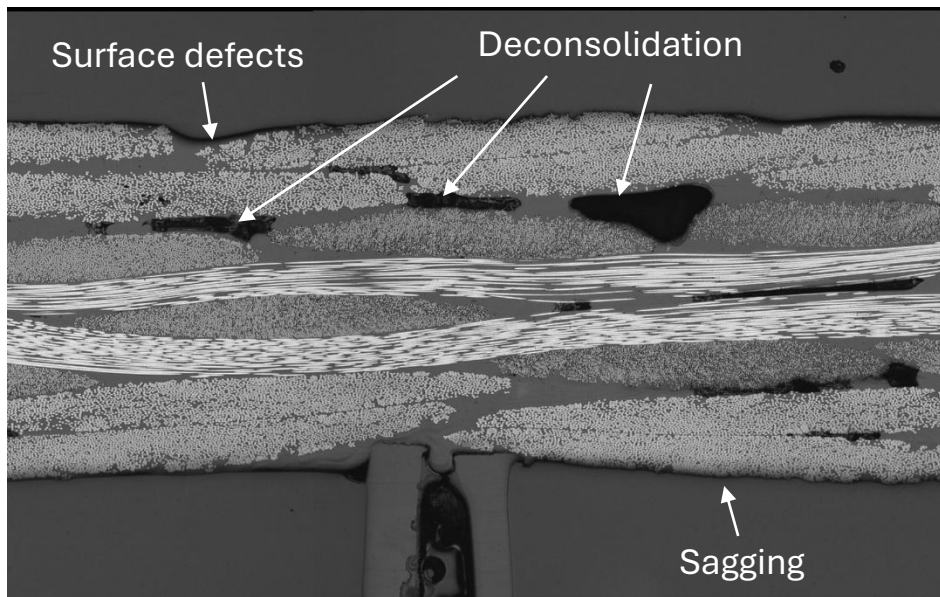


Figure 6: Optical cross section micrograph of a LM-PAEK skin sandwich. The facing was dried at 150°C and pressed at 290°C

While the PEI interlayer is clearly visible with the bare eye through its darker colour, it is indistinguishable in the micrographs in Figures 4 and 6, which neither show a matrix rich region in the bottom of the skin nor any distinguishable matrix phases. The PEI interlayer is then thought to diffuse into the bottom ply but retain a PEI-rich region there.

Crystallinity

The bulging of the facing observed in the previous section occurs when reaching the proper melting point of the matrix material. However, changes in the polymer constitution were observed at much lower temperatures. Notably, higher the processing temperature resulted in the skins appearing darker (see Figure 7).

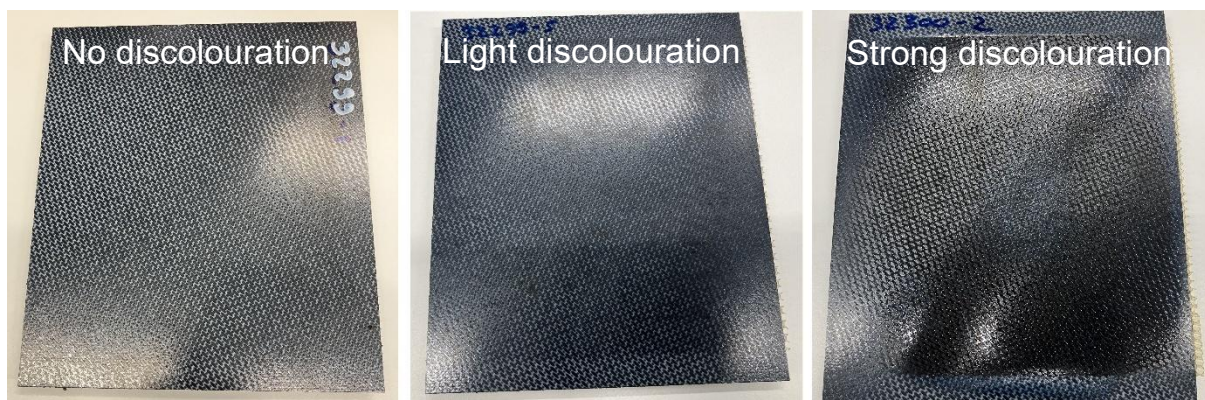


Figure 7: Sandwich panels with PEEK facing heated to 300°C, 310°C and 320°C, respectively (from left to right)

PEEK facings showed some discolouration from 310°C onwards while LM-PAEK skins exhibited a dark coloured surface at all processing temperatures. PAEK is desired to be crystalline in exterior applications due to higher chemical inertness. Therefore, DSC was carried out to determine the level of amorphousness, notably in the temperature range producing the highest interface strength (see

Flatwise Tensile Testing).

DSC data of the 300°C and 320°C processed facings displayed above is shown in Figure 8. The skin heated to 320°C shows a more distinct baseline shift at T_g followed by a minor exothermic peak at around 160°C. Both samples show a melt peak at 340°C but endothermic onset occurs later and much sharper when processing the skin at 300°C. This sample also exhibits a distinct secondary melt peak.

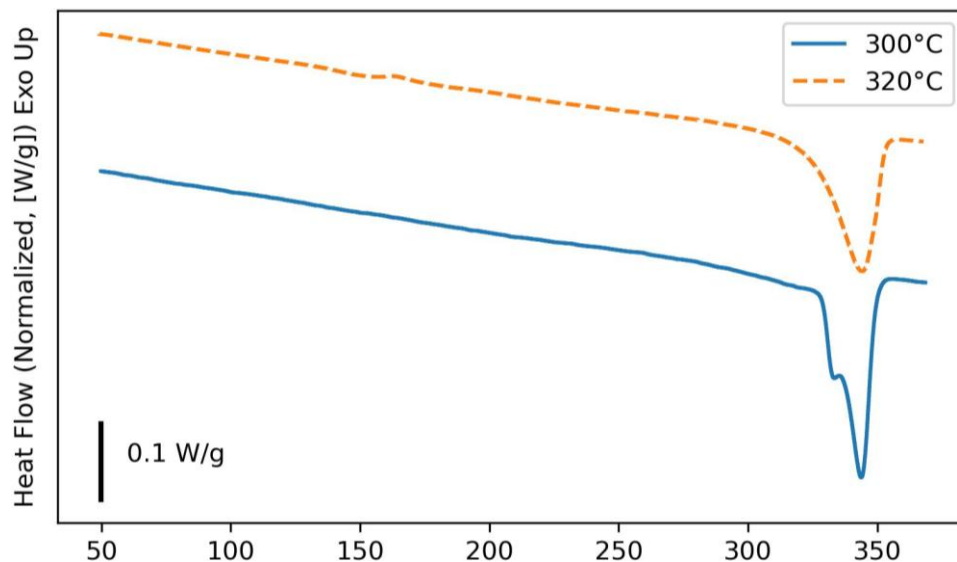


Figure 8: Differential scanning calorimetry of PEEK skins processed at 300°C and 320°C

The small exothermic recrystallisation peak indicates amorphousness in the discoloured 320°C processed sample, which is backed up by the much shallower endothermic onset at melt. The secondary melt peak in the 300°C sample is common in annealed PEEK with high crystallinity (19). It can be attributed to either a melting-recrystallisation-remelting mechanism or the presence of smaller lamellae dissolve at a slightly lower temperature (20). However, both skins display a large melting peak and lack the cold crystallisation peak characteristic of amorphous PEEK. (20). The partial amorphousness is then caused by gradual onset of melting below the true melting point dissolving parts of the crystal structure which cannot restore itself during the rapid cooling in the tooling. The DSC results however show that this phenomenon is marginal in PEEK and unlikely to cause the discolouration. Rather, changes in the surface morphology of the skin are likely to be the main cause.

Reducing the cooling rate through tooling adjustments could enable recrystallisation but would also result in a higher degree of core erosion. A shorter transition time between oven and press closure would result in reduced cooldown meaning the panel could be heated to a lower maximum temperature. Annealing the complete sandwich panel after completion would also increase the degree of crystallinity. As can be seen in the DSC data, recrystallisation occurs just after T_g meaning that annealing below the T_g of PEI is possible (21).

Flatwise Tensile Testing

Figure 9 shows the flatwise tensile strength achieved for sandwich panels fused at various temperatures. In the PEEK skin sandwich panels, fusion induced adhesion started to occur from 290°C onwards and then increased rapidly. The highest bond strength was achieved by heating to 320°C, beyond which it would decline again. Using PEEK face sheets with a 150 µm PEI film, flatwise tensile strengths in excess of 4 MPa were achieved, about half the strength of the reference panel made using adhesive bonding. For reference, conventional bonded aerospace grade sandwich panels using an aramid honeycomb core (Hexcel HRH-10 – 1/8 – 8.0; 128 kg/m³) achieve a flatwise tensile strength of 4.3 to 5.4 MPa (23). Grünewald et al. with their method presented in the introduction (13) achieved full core failure but due to the use of a foam core, this occurred at 2.2 MPa. At 110 kg/m³, the core density was about 20% lower than that of the tubular honeycomb in the present study. At 110 kg/m³ core density, the foaming method proposed by Provó Kluit (5) achieves a flatwise tensile strength of 5 MPa (24).

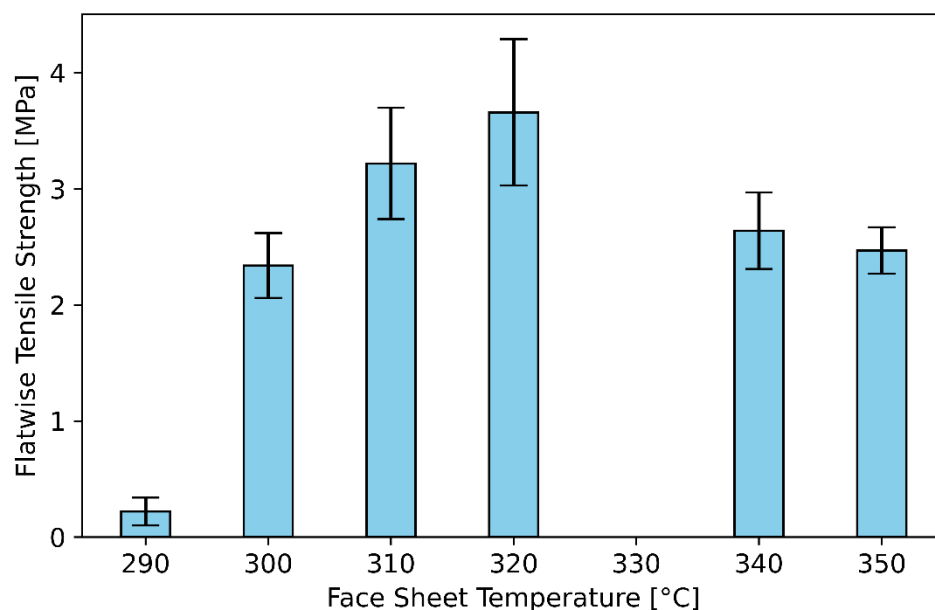
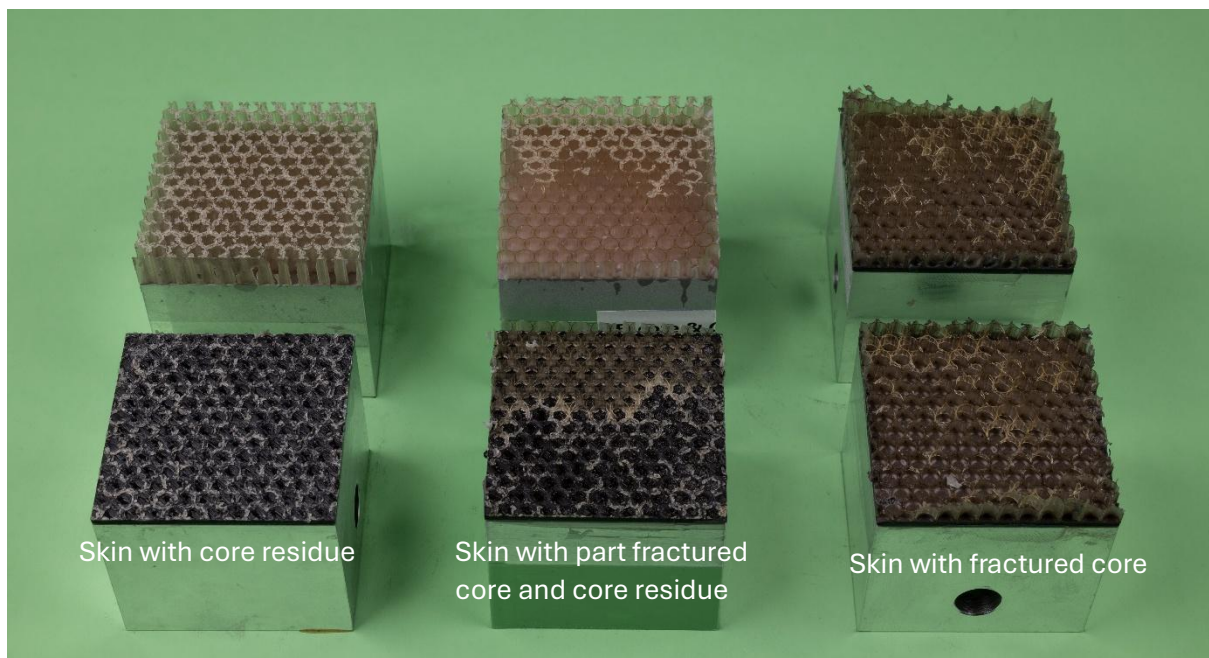


Figure 9: Flatwise tensile strength of PEEK sandwich specimens in terms of face sheet processing temperature

Initial trials with LM-PAEK at 290°C showed similar results as PEEK but higher temperatures resulted in an increase in the laminate defects observed in Figure 6. It was concluded that the processing window of LM-PAEK is less suitable for this method and the focus was placed on PEEK from that point on. However, if willing to accept some waviness in the facing, it is thought that good adhesion can be achieved with LM-PAEK as well.

The thickness of the interlayer was found to have no significant effect on the core-facing adhesion. Specimens processed at 350°C had similar flatwise tensile strength, irrespective of the interlayer thickness being 50 or 150 µm. The diffusion of the PEI interlayer into the bottom ply observed under the microscope could explain this behaviour, where more PEI will simply mix with the matrix instead of creating a thicker matrix rich zone for the core to bond with. Further tests were not carried out due to Grünewald et al. reaching the same conclusion in their comparative study on thermoplastic PEI foam core sandwich (13). However, omitting the interlayer altogether resulted in very poor adhesion, where the LM-PAEK skin pressed at 290°C without interlayer could easily be pulled off by hand while the same configuration with PEI film was well attached. The effects for PEEK skins are assumed to be comparable due to the high similarity between the two polymers.

Various failure modes were observed in the flatwise tensile specimens, depending on the processing temperature (see Figure 10). Pressing below 300°C resulted in clean separation of the core and skin, implying adhesive failure of the interface. When heating to between 300 and 310°C or to 340°C to 350°C, cohesive interface failure was observed with some core residue remaining on the skin. The higher the processing temperature, the more core residue was observed. Taking into account the observations from Figure 4, these findings show that the core separates from the facing at the point of contact directly above the cylinder wall, while the frayed core cylinder edges remain attached to the skin. The sample shown in Figure 6 on the other hand separates cleanly due to not having frayed. The 310°C and 320°C samples exhibited both regions of core facing cohesive failure and core tensile failure. These samples also displayed a much higher discrepancy in their results, as shown in Figure 9. Within the specimens exhibiting core fracture, samples with a greater region of core failure also had a higher flatwise tensile strength. The observation of core failure is remarkable as the adhesively bonded samples failed in the same mode but only at 8.16 MPa, about twice the load. The lower core tensile strength is likely the result of the core erosion and cracking observed in the previous section.



*Figure 10: Observed failure modes in flatwise tensile samples. From left to right:
Interface failure of a PEEK skin sample pressed at 350°C.
Partial core failure observed in PEEK skin specimen pressed at 320°C.
Full core failure in an adhesively bonded reference specimen (LM-PAEK skin).*

Conclusion

The present study successfully demonstrates the feasibility of creating fully thermoplastic sandwich panels by fusing the facings to the core. The proposed method makes use of a tubular PEI honeycomb and a thermoplastic face sheet made of a carbon fibre reinforced PAEK with a co-consolidated PEI interlayer. Infrared heating is used to warm the face sheet, followed by a rapid transition into a press, where the facing is fused to the core under pressure, while quickly cooling the face sheet to prevent core erosion. This method results in a strong thermoplastic bond without the need for adhesives.

The strength of the interface was evaluated using flatwise tensile testing. A flatwise tensile strength in excess of 4 MPa was achieved for sandwich panels processed around 320°C. Comparison with the flatwise tensile strength of products of other methods shows that despite the reduced performance with respect to the adhesively bonded reference sample, the present process manages to achieve competitive interfacial adhesion. Temperatures below and above the optimum resulted in poorer adhesion due to core erosion and insufficient bonding, respectively. Other factors also affected the processing window: Exceeding the melting point of the composite resin system caused the skin to deform over the uneven surface of the honeycomb core, while the PAEK matrix of the facings turned amorphous when (partial) melting occurred in the skin and the cooling rate was very high.

In the present configuration, PEEK clearly shows a higher suitability for the process than LM-PAEK as its melting point lies above the optimal processing window. However, good skin-core adhesion is thought to be achievable with both polymers as it was shown that with proper drying, it is possible to mitigate laminate defects even when exceeding the melting point. Possible amorphousness in the skin can be either accepted or removed with an annealing step below the T_g of PEI. The methodology developed in this study is not limited to the specific materials used, but can be broadly applied to various thermoplastic polymers. In an ideal scenario, using a matrix system in the facing that is identical to the core material would enable seamless integration and create unprecedented opportunities for end-of-life recycling and reuse of the sandwich structure. PEI skin-and-core sandwich panels would be highly suited for interior applications, while semi-crystalline configurations could be an alternative in exterior, structural parts.

A main advantage of the presented method is the short associated cycle time compared to conventional techniques requiring curing of both the skin matrix and the adhesive. Making a double sided flat sandwich in the present setup took about 20 minutes. When applying other fast processing techniques such as automated fibre placement or tape laying in combination with stamp forming to manufacture the skin laminates, a dedicated production line could go from prepreg to finished sandwich part in under one hour.

Despite achieving promising results, several challenges were identified that require further attention. A high flatwise tensile strength was attained, although failure occurred at least partially in the interface. Full core failure is preferable due to its greater predictability. Fraying of the core cylinder walls under pressure from the face sheet was shown to be highly detrimental to the core tensile strength. Future efforts should then focus on modifications to the core to increase the contact area, for instance by filleting the core edges. Furthermore, inconsistent heating of the facings in the IR oven proved to be a problem, leading to significant variability in the flatwise tensile strength. A dedicated industrial setup could be tailored to mitigate this issue, allowing for more uniform heating, even with larger skins.

Concluding, this research presents an innovative method for manufacturing thermoplastic sandwich panels. Importantly, the method allows for drastically reduced cycle times compared to conventional adhesive bonding methods. Further optimization of the processing parameters, core material selection, and heating methods is necessary to overcome existing challenges and achieve more predictable and reliable bond strength. Future efforts will focus on scaling up the technology to manufacture larger and more complex shapes.

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