INFLUENCE OF PROCESS PARAMETERS ON MECHANICAL PERFORMANCE OF THERMOPLASTIC MONO-POLYMER SANDWICH STRUCTURES

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Abstract

Thermoplastic mono-material composite sandwich structures can be essential in developing sustainable aircraft cabins. Compared to conventional structural materials, sandwich structures possess excellent mechanical performance and a higher stiffness-to-weight ratio. Additionally, thermoplastic materials are recyclable and weldable, have short processing cycle times, and have great potential for automated production.

The primary objective of this work is to characterize thermoplastic sandwich panels developed by three different manufacturing methods: isothermal, non-isothermal, and combined. The isothermal manufacturing process involves heating and bonding the sandwich components in a single step. In contrast, the non-isothermal approach separates the heating and bonding stages. The third manufacturing process combines both isothermal and non-isothermal approaches.

The mechanical performance of the sandwich structures concerning the manufacturing process parameters can be demonstrated using an experimental method. The drum peel tests are performed to determine the skin-core interfacial strength, and the flatwise compression and four-point bending test campaign is used to investigate the compression and bending behavior of sandwich panels. The failure mode can be altered from skin-core debonding to skin or core fracture by varying the process parameters such as temperature, pressure, and pressing time. The peel strength results for the three different manufacturing approaches differ drastically, while the bending strength results for the cases are similar and stay in the same range.

1. INTRODUCTION

The application of thermoplastic sandwich panels in the aviation industry can contribute to a reduction of CO_2 emissions. The thermoplastic sandwich structures obtain great potential for weight reduction and, thus, lower fuel consumption in aircraft. The structures with a honeycomb core and fiber-reinforced face sheets have outstanding mechanical performance and a great stiffness-weight ratio in comparison to conventional structural materials such as metals. Furthermore, thermoplastic materials are recyclable, which provides an essential contribution to environmental sustainability as well [1]. In order to simplify the recycling process, the mono-polymer structure is considered in this study, which is based on the same thermoplastic polymer for all sandwich elements. The usage of thermoplastic materials allows a great reduction in processing cycle times and an integration of additional functional elements such as ribs, inserts or brackets [2]. All processing steps, for example, compression molding, thermoforming, and integration of the functional elements can be combined in a so-called in-line production. This process optimization leads to energy efficiency, thereby contributing to a reduction of CO_2 emissions as well.

However, there are still several challenges in the manufacturing of thermoplastic panels. In previous studies, the manufacturing of sandwich panels was investigated, where two different production processes were proposed and could be validated by a microscopic bonding approach [3]. It was observed that two phenomena limit the process window. As shown in Figure 1, a higher temperature gradient in the sandwich structure has to be realized in order to achieve a sufficient fusion bonding quality. On the one hand, the skin-core interface shall be heated above the softening temperature of the polymer. On the other hand, the core should not be overheated and overloaded to avoid its collapse [3, 4].

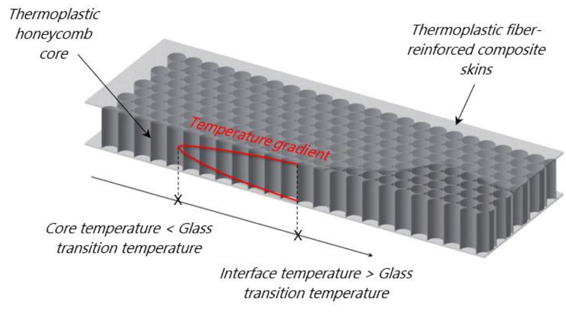


Figure 1. Temperature gradient required in a thermoplastic sandwich panel for defect-free manufacturing.

The main objective of this paper is to analyze the manufacturing process of thermoplastic mono-polymer sandwich panels with a honeycomb core and investigate the influence of the processing parameters on mechanical performance. The parametrical analysis helps to determine the optimal process window and leads to process stability.

2. METHODS AND MATERIALS

In order to produce an adhesive-free thermoplastic mono-polymer composite sandwich structure, several manufacturing methods are proposed. Furthermore, a parametric analysis using mechanical characterization was performed to verify the suggested process window and ensure process reproducibility.

2.1. Materials and Manufacturing

In this investigation, the thermoplastic polymer Polycarbonate (PC) was applied as the core and skin matrix material. In order to fulfill the specific flammability requirements for the aviation industry, the polymer was modified by the addition of halogen-free flame retardants. The commercially available fiber-reinforced skins with an 8-Harness satin textile weave structure were provided by Toray [5] and had a thickness of 0,48 mm. The honeycomb core had a tubular structure with a thickness of 10 mm and was supplied by Tubus Bauer [6].

The thermoplastic mono-material sandwich panels can be manufactured in three methods: isothermal, non-isothermal and combined [3]. The process is called isothermal when the heating and bonding are performed simultaneously. Once these two processes are separated, it is referred to as a non-isothermal case [7].

During the isothermal manufacturing process, the stack with the core and skins was transferred to the hot molding press, then heated and pressed in one step, as shown in Figure 2. To enable interfacial bonding, the molding press was pre-heated above the softening temperature of the polymer. The pressure was kept to a minimum to prevent the core collapse.

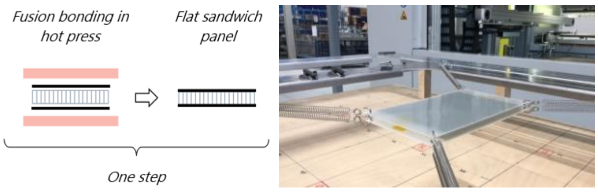


Figure 2. Isothermal manufacturing process.

In the non-isothermal manufacturing method, heating and fusion bonding are separated. This process consists of two steps, as shown in Figure 3. Firstly, the skin, attached to the tendering frame, was heated by infrared radiation and transferred to the cold molding press, where the cold core was already placed. In the second step, the entire sandwich panel was manufactured by the addition of the second pre-heated face sheet.

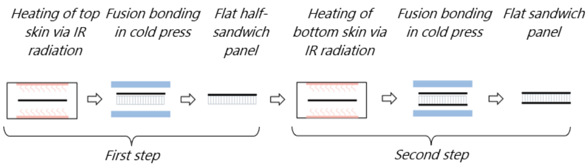


Figure 3. Non-isothermal manufacturing process.

The new approach was introduced by the combination of the previous isothermal and non-isothermal processes in order to develop the advantages of both processes and diminish their disadvantages. As illustrated in Figure 4, the skins and honeycomb core were fixed in the tendering frame and pre-heated by infrared radiation in one step. The core was distanced from the face sheets to avoid its melting, using an additional spring system. After the skins reached the required temperature, the structure was transferred to the hot molding press, which was heated below the softening temperature of the polymer.

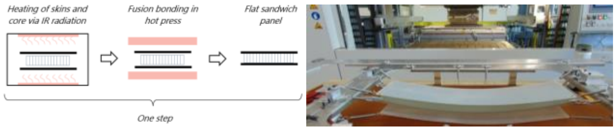


Figure 4. Combined manufacturing process.

2.2. Parametric analysis

The most influential process parameters were identified during the manufacturing feasibility tests for all three manufacturing methods. In the isothermal process, the main process factors are the preheating tool temperature, which varies from 180 °C to 200 °C, and the molding time, which ranges from 10 to 16 seconds. To prevent the core collapse, the molding pressure force was set to a minimum of 200 kN. For the mechanical characterization of the non-isothermal panels, the preheating IR temperature ranged from 280 °C to 320 °C, and the molding pressure force varied from 200 kN to 600 kN. The combined process is the mixture of the first two methods. Thus, the mechanical characterization was only performed for the optimal process parameters.

2.3. Drum peel test procedure

To characterize the bond strength between the skin and honeycomb core, the drum peel test was performed following the ASTM D1781 [8] and DIN EN 2243-3 [9] standards. As demonstrated in Figure 5, the ZwickRoell Z050 peeling apparatus included a flanged drum, flexible loading straps, and a suitable clamping device to secure the specimen. The flexible skin of the sandwich specimen was attached to a drum using a lower clamping device, which rolled upwards along the specimen, initiating debonding. The drum had a radius of 50 mm, and the flanges had a radius of 62.5 mm, resulting in an effective torque arm of 12.5 mm. The rotation of the drum along the sandwich specimen surface led to the debonding of the skin from the core in a stable manner under constant load [10].

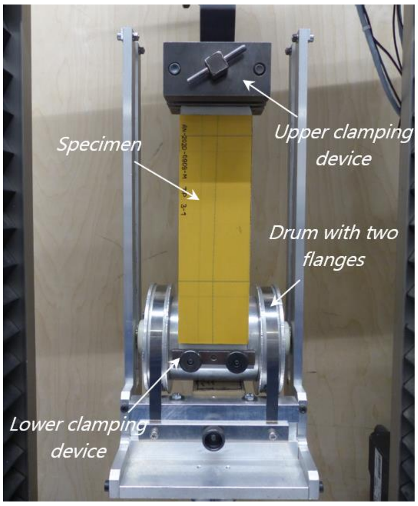


Figure 5. Experimental setup for the drum peel test.

Three different variants were defined for the testing to assess the impact of processing on the interfacial bonding degree: isothermal, non-isothermal, and combined. The dimensions of the sandwich specimens were 300 x 75 mm, and for each variant, six specimens were subjected to the peeling loads.

2.4. Flatwise compression test procedure

To determine the compressive strength of the sandwich panels, a flatwise compression test was performed according to the ASTM C365 [11] standard. The test was conducted at a crosshead speed of 0.5 mm/min and an initial force of 50 N. As demonstrated in Figure 6, a universal test machine, ZwickRoell Z050-K, with a loading plate diameter of 135 mm, was utilized for the trials.

The out-of-plane compression tests were performed on four variants: isothermal, non-isothermal, combined sandwich panels, and an original honeycomb core. The isothermal panels were manufactured at a pressing tool temperature of 190 °C with a molding time of 13 seconds. The IR temperature was set to 300 °C for the non-isothermal panel and 250 °C for the combined panel. In the combined process, the pressing tools were preheated to 135 °C, and the dimensions of the sandwich and honeycomb core specimens were 75 mm x 75 mm. Six samples were subjected to compression loads for each variant.

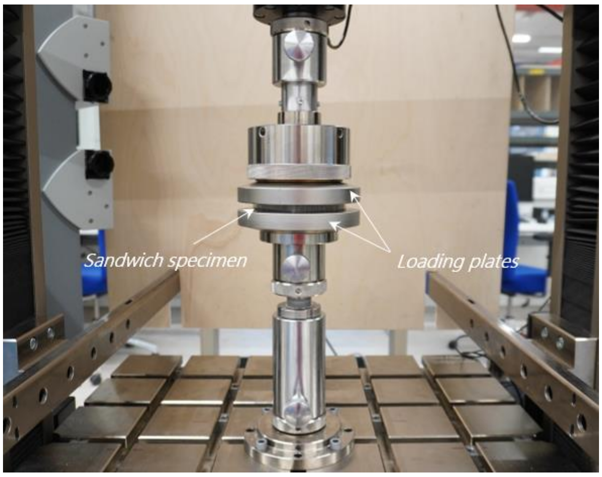


Figure 6. Experimental setup for the compressing test.

2.5. Four-point bending test procedure

The flexural properties of the thermoplastic sandwich panels were determined using a four-point bending test according to ASTM D7249 [12] and ASTM C393 [13]. As demonstrated in Figure 7, the test equipment included a Zwick/Roell Z050 universal load machine and a special loading fixture for the four-point bending test. This fixture consisted of loading and support bars, steel loading blocks, and rubbers. The test was performed at a crosshead speed of 6 mm/min and with a pre-load of 20 N. Four different variants were defined for the bending characterization: three thermoplastic variants (isothermal, non-isothermal, and combined) and one conventional thermoset variant. The isothermal panels were produced at a pressing temperature of 190 °C with a molding time of 13 seconds. The preheating IR radiation temperature for the non-isothermal panel was set to 300 °C, while the combined panel skins were preheated to 250 °C. The thermoset-based variant was produced using conventional pressing technology with a mold temperature of 140 °C and a curing time of approximately 50 minutes.

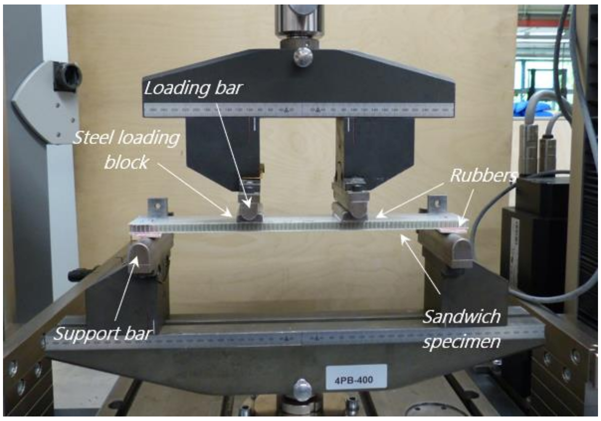


Figure 7. Experimental setup for the four-point bending test.

3. RESULTS AND DISCUSSION

3.1. Bonding Degree Characterization

The bonding parametric analysis demonstrated that all three manufacturing processes heavily depend on the applied temperature. As depicted in Figure 8, the bonding degree was increased threefold, while the interfacial temperature was changed from 165 °C to 280 °C. The transition between all three manufacturing approaches can be clearly seen, increasing the processing temperature. In the isothermal process, increasing the tool temperature from 180 °C to 200 °C doubled the bonding degree, while in the non-isothermal process, a 40 °C increase in IR temperature raised the bonding degree from 0.24 to 0.37.

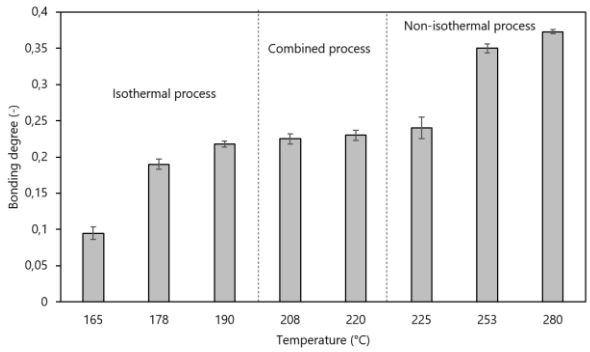


Figure 8. Bonding vs. processing temperature curve.

A significant influence of the molding time was observed in the isothermal process, which is attributed to the heat transfer process during manufacturing and the continuous healing process even after compression molding. Figure 9 depicts the bonding fracture toughness as a function of pressing time. Increasing the molding time from 10 to 13 seconds raised the fracture toughness from 350 J/m^2 to 475 J/m^2. However, a further increase in molding time by 3 seconds did not lead to a significant improvement in bonding fracture toughness, which only increased to 494 J/m^2.

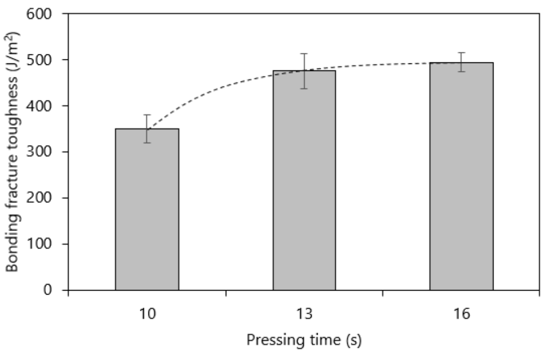


Figure 9. Fracture toughness vs. pressing time curve for the isothermal process at a tool temperature of 190 °C.

As the applied pressure force should be set to a minimum, namely 200 kN, to prevent the core collapse, only the influence of pressing time was investigated in the isothermal process. However, higher pressure was found to have a positive effect on the bonding degree in the non-isothermal process, which can be explained by the improved contact surface at the skin-core interface governed by the intimate contact mechanism. Figure 10 illustrates the changes in the bonding fracture toughness with increased pressure force. Applying the minimum possible pressure force in the machine, 200 kN, yielded a fracture toughness of 940 J/m^2. The further increase in the pressure force to 400 kN improved the fracture toughness by only 10%. However, a pressure force of 600 kN results in the highest enhancement of the bonding fracture toughness, namely 1506 J/m^2. The further increase in pressure was critical due to the limited compressive strength of the honeycomb core.

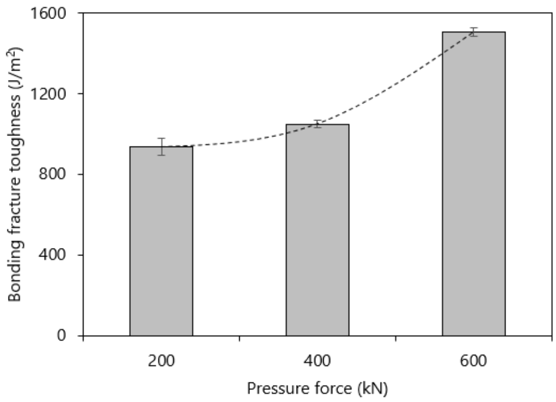


Figure 10. Fracture toughness vs. pressure force curve for the non-isothermal process at an IR temperature of 300 °C.

The combined process, a combination of the previous two manufacturing methods, reflects the impact of process parameters from both isothermal and non-isothermal processes.

3.2. Flatwise Compression Behavior

The out-of-plane compressive strength characterization was performed for four different variants: isothermal, combined, non-isothermal sandwich panels, and the original honeycomb core. Figure 11 depicts the recorded force-displacement curves for the four sandwich panel variants. The original core displayed an elastic deformation behavior until it fractured at 16.8 kN. The isothermal and combined sandwich panels exhibited similar behavior, with the isothermal variant failing at 12.2 KN and the combined variant fracturing at 14.3 kN. The non-isothermal sandwich structure showed different deformation behavior, reaching a maximum of 7.3 kN during elastic deformation and then deforming plastically to obtain a second maximum at 8.1 kN. However, since it did not fracture as the other variants did, the compression test was stopped at a crosshead displacement of 2 mm.

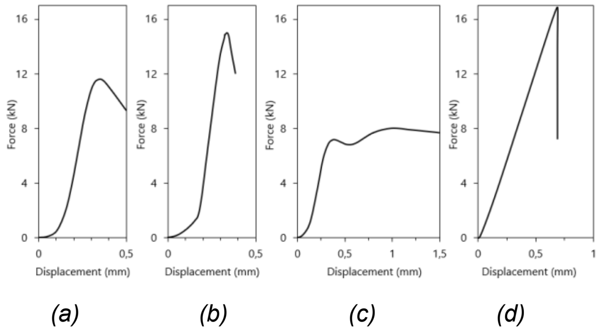


Figure 11. Force vs. crosshead displacement curve for an isothermal panel (a), combined panel (b), non-isothermal panel (c), and virgin honeycomb core (d).

Figure 12 depicts the out-of-plane compression strength obtained for four different variants. The original honeycomb core obtained the highest compressive strength value of 2.94 MPa. While the combined panel achieved almost 90% of the original core's compressive strength, the isothermal variant demonstrated a decrease of 22% compared to the honeycomb core. The non-isothermal sandwich structure exhibited the highest drop in compressive strength, with a 50% decrease from the original core's strength.

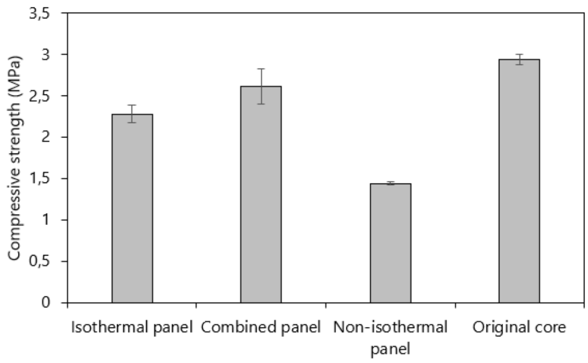
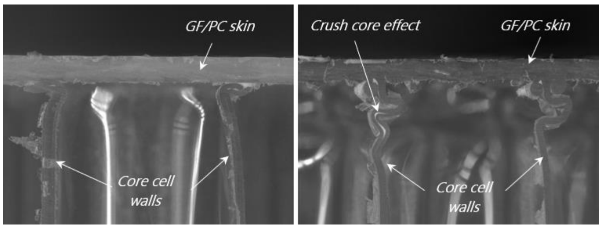


Figure 12. Compressive strength of the sandwich panels (produced isothermally, combined, and non-isothermally) and the original honeycomb core.

The reduced compressive strength of the non-isothermal variant can be attributed to the crushing of the honeycomb core during the process. The crushed core pressing technology is a common process in sandwich production with conventional thermoset-based composite materials. However, it negatively affects the mechanical performance of the sandwich panel. This phenomenon has been well-described by Dulieu-Barton et al. [14] for sandwich structures with a Nomex® honeycomb core. Figure 13 illustrates the crushing of the honeycomb core during the isothermal and non-isothermal processes. The core walls were melted and partially compressed at the interface in the isothermal panel. However, core crushing did not occur when the core was heated during the compression molding process, as this helped the core walls prevent global crushing. In contrast, during the non-isothermal process, almost the entire honeycomb core remained cold, with only local heating at the interface. As a result, the honeycomb core reached the end of the elastic range and transitioned to the plastic deformation range during the compression molding. This deformation determined the crush core effect, which contributed to the reduction of the mechanical performance of the non-isothermal variant.



(a) (b)

Figure 13. Crushed honeycomb core of the isothermal (a) and non-isothermal panel (b).

3.3. Bending Behavior

The flexural properties of the sandwich panels were determined using a four-point bending test. Three thermoplastic variants were produced: isothermal, combined, and non-isothermal. In addition, the conventional thermoset-based panel was subjected to the bending loads to compare the two types of polymer systems. Figure 14 presents the flexural properties of the four sandwich variants and shows that the highest flexural strength of 63 MPa was achieved by the combined variant. The ultimate bending strength of the isothermal panel was 55 MPa, while the non-isothermal and thermoset-based variants yielded a similar bending strength at 50 MPa. Despite its relatively high bending characteristics, the standard deviation of the isothermal variant was the highest, namely 8.2 MPa, compared to the other variants. The lowest scatter of 2.9 MPa was demonstrated by the combined sandwich structure, while the non-isothermal and conventional panels had a standard deviation of approximately 4 MPa. The relatively low mechanical performance of the non-isothermal and conventional sandwich structure can be explained by the crush core phenomenon, which reduces the compressive strength and influences flexural behavior.

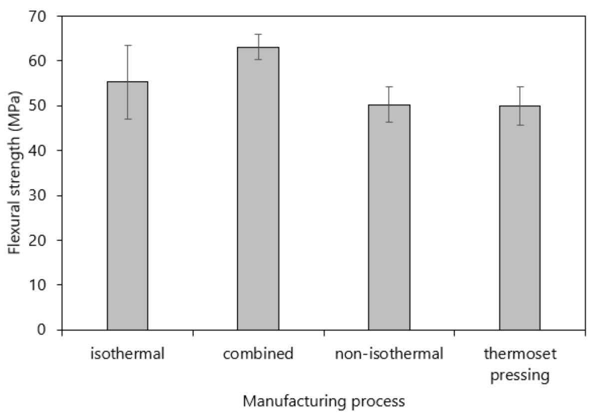


Figure 14. Flexural properties of thermoplastic (produced isothermally, combined, and non-isothermally) and thermoset panels.

Consequently, the failures that occurred were investigated to gain a better understanding of the governing mechanisms during the bending deformation. All of the isothermal panel specimens failed due to interfacial debonding, and the separation of the upper skin from the honeycomb core was frequently observed between the loading bars, as shown in Figure 15. However, several specimens failed outside of the loading bars.

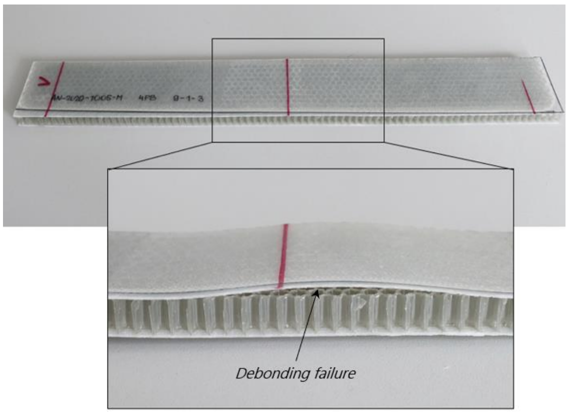


Figure 15. Exemplary isothermal panel after the bending test.

Figure 16 and Figure 17 depict examples of non-isothermal and combined specimens after the bending test, respectively. Both types of specimens exhibited similar failure modes, including fiber fracture, compression, and shear failure of the core. The majority of the samples failed outside the loading bars. Furthermore, it was observed that only the upper face sheet failed, while the lower face sheet remained undeformed.

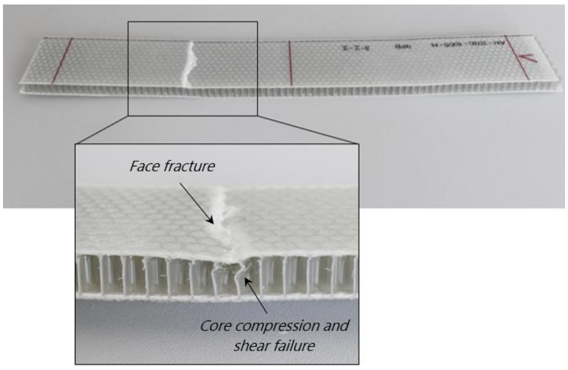


Figure 16. Exemplary non-isothermal panel after the bending test.

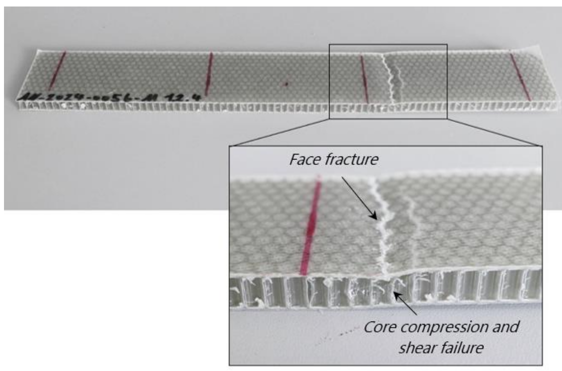


Figure 17. Exemplary combined panel after the bonding test.

In the next step, the parametric analysis was also performed for the flexural characterization of the sandwich structures. Initially, the impact of the applied temperature was investigated, and in the isothermal process, increasing the molding temperature significantly improved the flexural strength. As shown in Figure 18, the isothermal panel obtained a flexural strength of 21 MPa at a pressing tool temperature of 180 °C. With just a 10 °C increase in temperature, the flexural strength surged to 54 MPa. However, a further increase in the temperature did not lead to significant improvements in strength, as it peaked at 59 MPa.

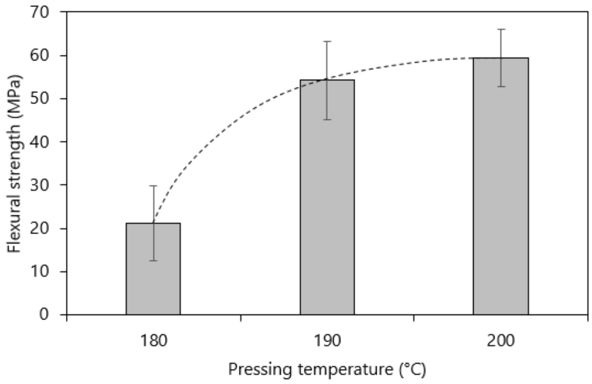


Figure 18. Influence of the pressing temperature on the panel flexural properties for the isothermal process at a molding time of 13 seconds.

The increase in the applied temperature in the non-isothermal process did not significantly impact the flexural properties. As depicted in Figure 19, the bending strength increased from 48 MPa to 51 MPa with the increased temperature of 40 °C. However, the increase rate remained at 10%.

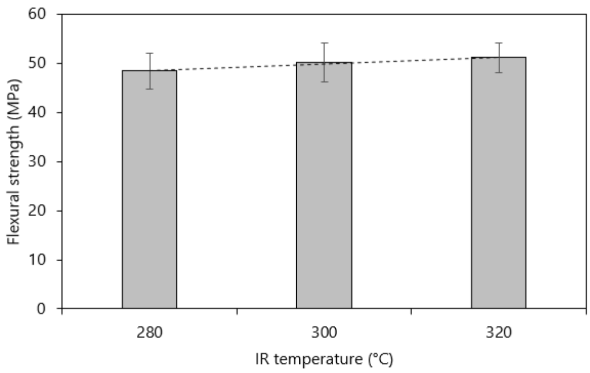


Figure 19. Dependence of flexural properties on the IR temperature for the non-isothermal process.

Finally, the impact of the applied molding time was analyzed for the isothermal process. Figure 20 illustrates the dependence between the bending strength and the applied molding time at a press tool temperature of 190 °C. The results show that the flexural strength significantly improves when the molding time is increased to 16 seconds. In this case, the strength increased by 8% compared to the strength at 10 seconds of molding. However, a further increase in the molding time led to the core collapse.

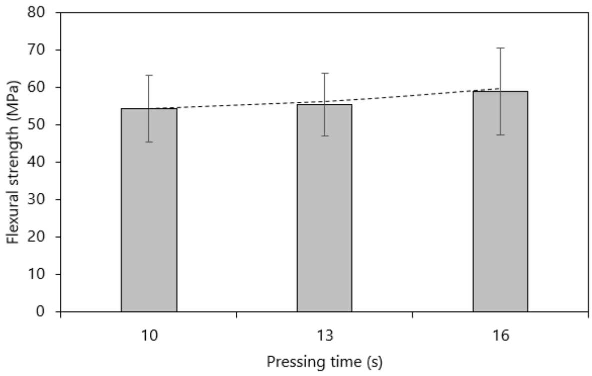


Figure 20. Influence of the pressing time on the panel flexural properties for the isothermal process at a pressing tool temperature of 190 °C.

4. CONCLUSION

This paper has described several manufacturing methods for thermoplastic mono-polymer sandwich structures with a honeycomb core and revealed the influence of the process parameters on mechanical performance. It was found that the bonding quality of the sandwich structure is significantly affected by the applied temperature and time in the isothermal process. In the non-isothermal process, the higher pressure improved the bonding quality as well as the IR temperature. The out-of-plane compression strength was notably reduced in the non-isothermal process, which can be attributed to the crushing of the honeycomb core, subsequently influencing the bending performance. The non-isothermal panel attained 91% of the flexural strength of the isothermal variant, while the combined panel achieved the best results, displaying 1.25 higher bending strength than the non-isothermal variant. Additionally, it was shown that the bending performance can be improved by increasing the temperature applied in the isothermal process. The improvement of 57% in the flexural strength was demonstrated by changing the temperature from 180 °C to 200 °C.

Thus, these findings highlight the importance of considering the molding temperature, pressure, and time as key process parameters in the sandwich manufacturing process that can significantly impact the mechanical performance of the final product. Furthermore, the mechanical analysis demonstrated that the combined manufacturing process is more robust and provides better mechanical performance of the final product compared to the isothermal and non-isothermal manufacturing methods.

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