Toward High-Quality In-Situ Consolidation of Thermoplastic Composites: Heated-Mandrel AFP with Controlled Vacuum Cooling

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Abstract:

Automated Fiber Placement (AFP) with in-situ consolidation is an attractive route for rapid manufacturing of thermoplastic composite structures; however, laminate quality is often limited by two defect classes: macroscale warpage and microscale voids. Practitioners commonly mitigate warpage using heated mandrels, but elevated tool temperatures can adversely affect void evolution and push void content beyond aerospace acceptance limits. This study addresses this trade-off for CF/LMPAEK by introducing a coupled heated-mandrel + vacuum-bagged cooling procedure designed to achieve simultaneously low curvature and aerospace-grade void content.

A heated mandrel is used during deposition, with tool temperature regulated slightly above the polymer glass transition temperature (Tg). Upon completion of AFP, the laminate is vacuum bagged while maintaining the temperature. The assembly is held for a 1-hour dwell, after which the heating system is switched off; the laminate then cools to room temperature naturally under vacuum. Laminate quality is benchmarked against (i) a reference laminate manufactured on a cold tool and (ii) a laminate produced on a heated mandrel without vacuum-bagged cooling.

Heated tooling reduces warpage dramatically: the measured curvature decreases to approximately one-ninth of the cold-tool reference, independent of whether vacuum-bagged cooling is applied. In contrast, void content exhibits a dependence on the post-deposition pressure history. The cold-tool reference achieves 0.31% voids, while heated-mandrel processing without vacuum cooling increases void content to 1.85%, exceeding the typical 1% aerospace criterion. The proposed vacuum-bagged cooling strategy restores laminate quality, reducing void content to 0.67% (approximately one-third of the heated-mandrel-only approach) while preserving the low-warpage benefit.

These results demonstrate that the processing pathway for in-situ consolidated CF/LMPAEK laminates can reconcile warpage suppression with aerospace-grade void content, enabling higher-quality thermoplastic AFP structures without a conventional autoclave cycle.

1. Introduction

Carbon-fiber-reinforced thermoplastic composites are increasingly considered for high-performance structures because they combine the specific stiffness and strength of continuous-fiber laminates with matrix-level advantages such as weldability, repairability, recyclability, toughness, and reprocessability at elevated temperature. Automated fiber placement (AFP) further extends these advantages by enabling repeatable, accurate, and material-efficient deposition of narrow prepreg tapes over large or geometrically complex tools [1,2]. For thermoplastic composites, AFP is especially attractive because heating, placement, and consolidation can in principle be combined into a single in-situ consolidation step, reducing dependence on autoclave or press-based secondary processing. Nevertheless, the same short thermal and mechanical cycle that makes AFP attractive also makes laminate quality highly sensitive to processing history [1,3]. Experimental studies have consequently shown that interlaminar properties and porosity are strongly affected by thermal conditions, including heating level, layup speed, and tool temperature [1,4].

Among the defects that hinder the broader adoption of in-situ consolidated thermoplastic AFP, voids are especially detrimental because they promote local stress concentrations and crack initiation, ultimately compromising interlaminar shear strength [5]. Heathman et al. [1] reported that void content should be minimized to approximately 1% or below for critical applications, and showed that low void content can be achieved in CF/LM-PAEK under suitable in-situ consolidation conditions. Chen et al. [4] found for CF/PPS laminates that interlaminar void content dominated mechanical performance more strongly than crystallinity, and that autoclave post-consolidation improved interlaminar shear strength by reducing voids and modifying crystallinity.

Dimensional stability represents a second and different quality requirement because a laminate may exhibit low porosity while still being unacceptable due to warpage or residual-stress-driven distortion [6]. Warpage in thermoplastic AFP is associated with steep thermal gradients, anisotropic thermal expansion, nonuniform shrinkage, and residual stress development during rapid heating and cooling [7]. Zhang et al. [6] showed that consolidation temperature, consolidation force, and consolidation speed strongly influence warpage and residual stress in CF/PEEK laminates, demonstrating that dimensional accuracy is a process-dependent outcome rather than only a material property. Previous works have also indicated that increasing the tool or mandrel temperature can reduce warpage in parts with free edges by reducing thermal gradients and cooling-rate severity [1,6]. However, a heated tool mainly modifies the thermal history, whereas void suppression also requires an adequate pressure history after the moving compaction roller has passed [1,8].

Despite these advances, the literature has largely treated warpage reduction and void suppression as separate optimization problems: heated tooling is commonly discussed for dimensional stability, while post-processing or vacuum consolidation is typically discussed for porosity reduction. The unresolved issue is whether the dimensional benefit of a heated mandrel can be retained while the void penalty associated with insufficient post-deposition pressure history is suppressed. In this work, a coupled heated-mandrel and controlled vacuum-bagged cooling procedure is proposed for in-situ consolidated CF/LM-PAEK laminates. The approach uses a mandrel maintained near the glass transition temperature during AFP to reduce warpage, followed by vacuum-bagged dwell and cooling to extend consolidation pressure during the critical post-deposition thermal stage. By comparing cold-tool AFP, heated-mandrel AFP, and heated-mandrel AFP with vacuum-bagged cooling, this study aims to clarify how thermal and pressure histories can be combined to achieve both low macroscale curvature and aerospace-grade microscale void content.

2. Experimental Procedure

2.1 Material and AFP manufacturing setup

The material used in this study was carbon-fiber-reinforced low-melt polyaryletherketone tape (CF/LM-PAEK). The tape width was 0.25 in, and the measured fiber volume fraction was 51%. The glass transition temperature of the LM-PAEK matrix is 149 °C. This temperature was used as the basis for selecting the heated-mold processing condition, since maintaining the laminate slightly above the glass transition temperature can increase molecular mobility and reduce thermally induced residual stresses while avoiding the high temperatures required for remelting.

The laminates were manufactured using the hot-gas-torch-assisted robotic AFP system at Concordia University. The AFP system was developed by Automated Dynamics (Trelleborg). A photograph of the AFP head and heatable steel mandrel is provided in Figure 1. The heated mandrel consisted of a heater positioned beneath the steel table and a PID temperature controller, which regulated the tool surface temperature.

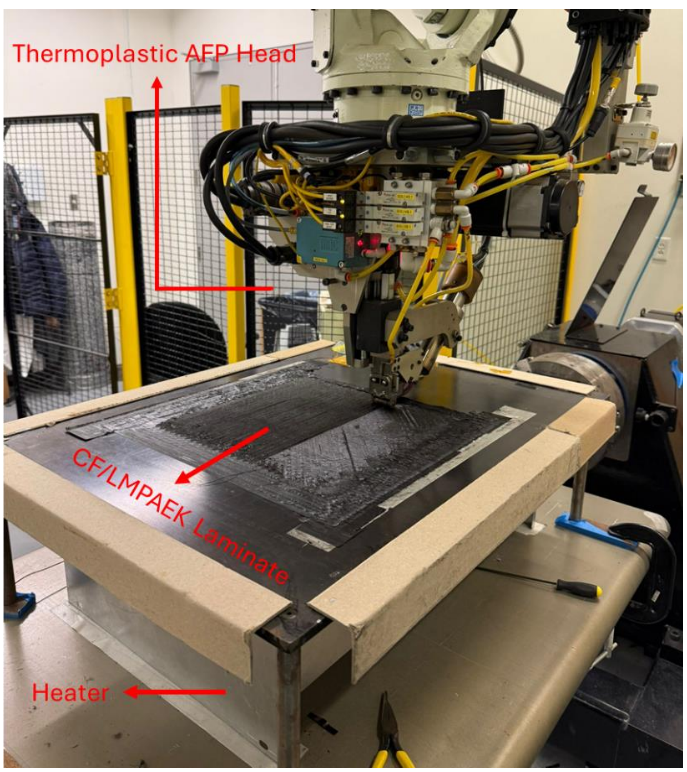

Figure 1. Hot-gas-torch-assisted robotic automated fiber placement (AFP) setup used for CF/LM-PAEK laminate manufacturing at Concordia University

Square laminates were manufactured using the same stacking sequence, [0/+45/−45/90]s, for all processing conditions. To isolate the effect of mold temperature and post-deposition vacuum cooling, the AFP process parameters were kept constant for all laminates. The hot gas torch temperature was 800 °C, the gas flow rate was 60 SLPM, the compaction force was 60 lbf, and the layup speed was 2 in/s.

2.2 Processing routes

Three processing routes were investigated. The first route was deposition on the mold with the heater switched off, referred to here as the cold-mold condition. In this case, the laminate was deposited on the unheated mold and allowed to cool naturally after AFP. This condition was used as the baseline case for comparison.

The second route was deposition on the heated mold without subsequent vacuum-bagged cooling. In this condition, the mold temperature was set to 155 °C and actively controlled during the entire AFP manufacturing process. After completion of deposition, the mold was maintained at 155 °C for one hour. The heater was then switched off, and the laminate cooled on the mold until the temperature decreased below 50 °C, which required approximately one hour. This condition was used to evaluate the effect of heated tooling on laminate distortion and void content in the absence of post-deposition vacuum pressure.

The third route was deposition on the heated mold followed by vacuum-bagged cooling. As in the second route, the mold temperature was controlled at 155 °C during AFP manufacturing. Immediately after deposition, the laminate was vacuum bagged while remaining on the heated mold. The vacuum was maintained while the mold temperature was held at 155 °C for one hour. The heater was then switched off, and the laminate was cooled under vacuum until the temperature decreased below 50 °C, which required approximately one hour. This route was designed to combine the warpage-reduction benefit of heated tooling with an extended post-deposition pressure history during the temperature range in which the matrix remained sufficiently mobile for void evolution. Figure 2 represents the vacuum-bagged cooling configuration of laminate after the AFP deposition.

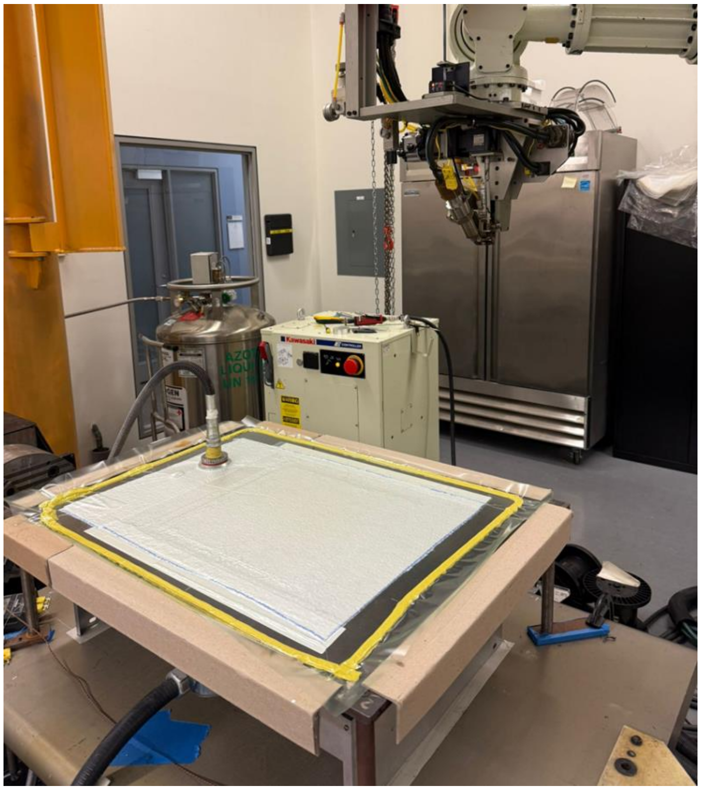

Figure 2. Vacuum-bagged cooling configuration applied after AFP deposition on the heated mandrel.

3. Characterization Methods

3.1 Curvature measurement

It should first be noted that, for all laminates, no warpage was observed during manufacturing because the laminate edges were constrained by the mold using double-sided high temperature adhesive tapes. Therefore, warpage measurements were performed only after the laminates had been released from the mold and cut into 7 in × 7 in square laminates. A photograph of the three manufactured laminates is shown in Figure 3 to provide a direct visual comparison of the final shapes. This figure is intended to demonstrate the macroscopic effect of the different processing routes before quantitative curvature values are presented.

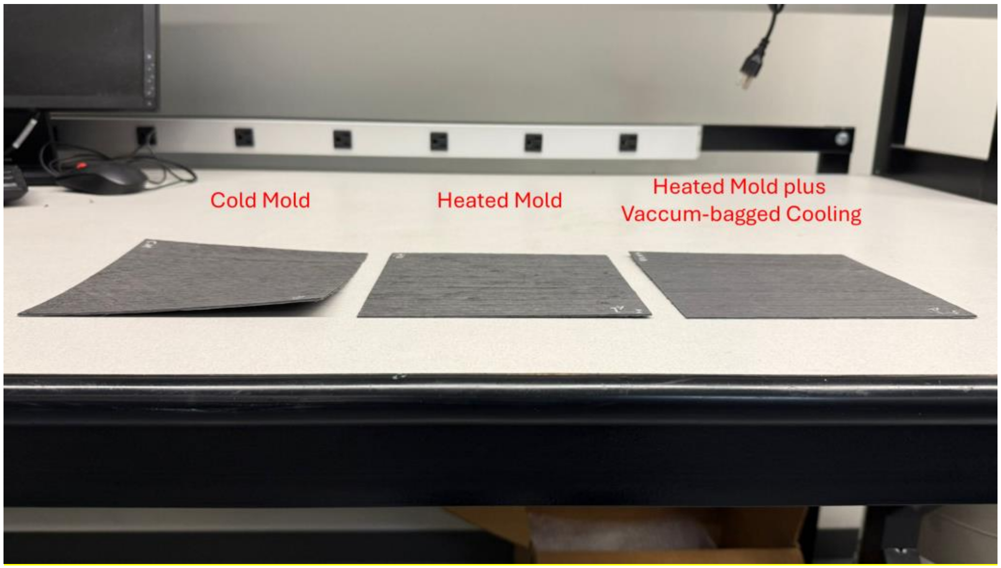

Figure 3. Visual comparison of [0/+45/−45/90]s CF/LM-PAEK square laminates manufactured using three processing routes: cold mold, heated mold, and heated mold followed by vacuum-bagged cooling.

The warpage of the manufactured laminates was quantified by measuring the out-of-plane corner deflection. It was observed that the warpage occurred predominantly along one diagonal direction of the square laminate, while the curvature along the other diagonal was negligible. Therefore, the laminate deformation was approximated as cylindrical bending along the dominant diagonal direction. For the measurements, one corner of the laminate was pressed against a flat reference surface, and the vertical position (height) of the opposite corner was measured. The diagonal distance between the constrained corner and the lifted corner was 250 mm for all laminates. Assuming constant curvature along this diagonal direction, the deformed shape was approximated as a circular arc. The radius of curvature was determined using the geometric relations

$$h = R(1 - cos\ \theta) \tag{1}$$

and

$$L = Rsin\ \theta \tag{2}$$

where h is the measured corner deflection (height), L is the diagonal distance between the constrained and lifted corners, R is the radius of curvature, and θ is the corresponding central angle. Eliminating θ yields

$$R = \frac{L^2 + h^2}{2h} \tag{3}$$

3.2 Void evaluation

Void content was evaluated using polished cross-sections taken from laminates manufactured under the three processing conditions. Representative micrographs were acquired from each condition, as shown in Figure 4.

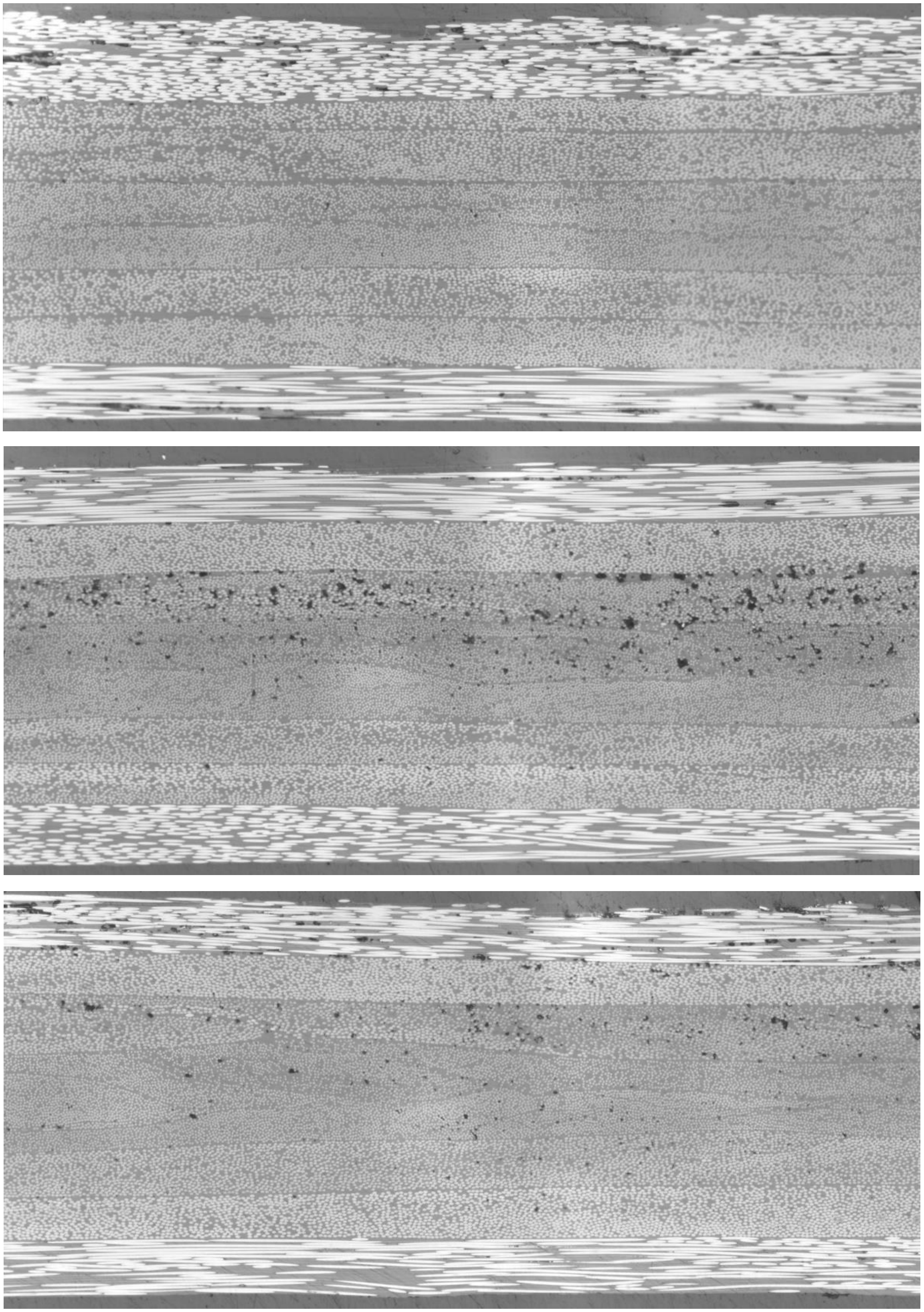

Figure 4. Cross-sectional micrographs of CF/LM-PAEK laminates manufactured under the three processing routes: cold mold, heated mold, and heated mold followed by vacuum-bagged cooling, shown from top to bottom, respectively.

4. Results and Discussion

4.1 Effect of heated mold on laminate curvature

Using the measured corner deflections of 31.53 mm, 3.27 mm, and 3.38 mm for the laminates made on cold mold, heated mold, and heated mold plus vacuum bagging, respectively, the corresponding radii of curvature were calculated as 1007 mm, 9558 mm, and 9249 mm, as per formulation presented in the previous section. For comparison, the distortion curvature may also be expressed as the inverse of the radius of curvature. The cold-mold laminate exhibited the largest distortion among the three processing routes. This behavior is expected because deposition on a cold tool causes rapid and nonuniform cooling after each tow is placed. The resulting thermal gradients and shrinkage mismatch between plies promote residual-stress development, which becomes visible as macroscopic warpage after the laminate is removed from the mold. In contrast, both heated-mold conditions produced substantially flatter laminates. Maintaining the mold at 155 °C during deposition reduced the severity of the thermal gradient between newly deposited material and the underlying laminate/tool system. Since 155 °C is slightly above the glass transition temperature of the LM-PAEK matrix, the laminate remained in a thermally softened state during manufacturing and during the one-hour post-deposition dwell. This allowed partial stress relaxation before final cooling. As a result, the final curvature was strongly reduced compared with the cold-mold reference. The similarity in curvature between the heated-mold-only laminate and the heated-mold plus vacuum-cooled laminate indicates that the main factor controlling macroscopic distortion was the mold temperature history rather than the vacuum condition.

4.2 Effect of processing route on void content

Although heated tooling improved laminate flatness, it did not by itself guarantee low void content. The cold-mold laminate showed the lowest void content, approximately 0.31%. In comparison, the heated-mold-only laminate showed a substantially higher void content of approximately 1.85%, exceeding the common 1% quality threshold used for high-performance aerospace laminates. This result demonstrates that reducing warpage and reducing void content are not necessarily achieved by the same processing condition. The increase in void content for the heated-mold-only condition can be explained by the post-deposition thermal and pressure history. During AFP, compaction pressure is applied only locally under the roller and only for a short time. In the heated-mold condition, the laminate remains above the glass transition temperature after the roller has passed. Under this condition, the polymer matrix still has mobility, but the roller pressure is no longer present. Therefore, voids that were collapsed during the brief compaction stage may grow or re-open during the subsequent high-temperature dwell.

The vacuum-bagged cooling route reduced the void content to approximately 0.67%, which is below the 1% target and approximately one-third of the void content measured in the heated-mold-only laminate. This improvement indicates that the vacuum stage provided a beneficial post-deposition pressure history. The one-hour dwell at 155 °C under vacuum likely allowed suppression of voids before the laminate cooled below the temperature range where matrix mobility became limited.

5. Conclusions

A heated-mold AFP route with controlled vacuum-bagged cooling was investigated for CF/LM-PAEK laminates. The results reveal a clear distinction between two defect-control mechanisms. Mold heating primarily controlled the macroscopic shape of the laminate by reducing thermal gradients and allowing stress relaxation. Vacuum-bagged cooling primarily controlled the microscale void content by extending the pressure-assisted stage beyond the short roller contact time. The cold-mold route provided low void content but high distortion. The heated-mold-only route provided low distortion but excessive void content. The proposed heated-mold plus vacuum-cooling route achieved both low distortion and void content below 1%. This processing sequence therefore reconciles two requirements that are often difficult to satisfy simultaneously in in-situ consolidated thermoplastic AFP: dimensional stability and low porosity. The results suggest that heated tooling should not be viewed as a complete consolidation solution by itself. Instead, it should be combined with a post-deposition pressure strategy when the laminate remains above or near the glass transition temperature after deposition. Future work should include mechanical characterization of the manufactured laminates, particularly short-beam shear (SBS) testing for interlaminar shear strength (ILSS), which would provide more direct performance-based criteria.

6. References

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