EFFECT OF DEPOSITION RATE ON MECHANICAL PROPERTIES OF AN IN-SITU CONSOLIDATED LM-PAEK LAMINATE MADE WITH LASER AUTOMATED FIBER PLACEMENT

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ABSTRACT

While automated fiber placement (AFP) is a standard aerospace composite manufacturing process, adoption and adaptation of these technologies have been slower for cost and rate sensitive applications and industries, such as marine and automotive. Reducing or eliminating large capital investment requirements such as ovens and autoclaves may make AFP a more approachable option for a wider range of industries, especially if suitable mechanical properties can be achieved at high deposition speeds to reduce manufacturing times for large structures. In-situ consolidation of thermoplastic laminates allows for the elimination of expensive and time-consuming post-processing steps, such as autoclave or vacuum-assisted oven consolidation, often required for aerospace applications. In this study, a carbon fiber/ LM-PAEK™ thermoplastic laminate was manufactured at four different deposition rates ranging from 0.085-0.847m/s using robotic 8-lane laser-based thermoplastic AFP equipment, then subsequently tested to determine the effect of deposition rates on mechanical properties. Tensile and compressive properties are presented and discussed as a function of deposition speeds.

Keywords: AFP, automated fiber placement, composites, maritime, in-situ consolidation, LM-PAEK™, thermoplastic

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1. INTRODUCTION

Automated fiber placement (AFP) of thermoplastic materials offers advantages in the manufacture of relatively complex components and structures regarding repeatability, material consumption efficiency, and improved layup rates over other manufacturing processes [1]. Thermoplastics offer further advantages over thermoset manufacturing by eliminating the need for post-processing in autoclaves due to the option for in-situ consolidation [2]. Research has been conducted into increasing the deposition rate of thermoplastic materials using in-situ consolidation and understanding the relationship between processing speed and mechanical performance of the resulting laminates at deposition rates up to 7.5m/min (0.125m/s) [2, 3, 4]. While sufficient in-situ consolidation at rates above 0.5m/s may offer the possibility of eliminating the need for autoclave post-processing for commercial aerospace components [2], further understanding of the

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performance of newer material technologies such as Victrex's low-melt polyaryletherketone (LM-PAEK™) would advance the state of the art in higher-rate thermoplastic AFP manufacturing. This paper seeks to investigate the relationship between deposition rate and mechanical performance of this material at rates up to 0.847m/s (50.8m/min).

2. EXPERIMENTATION

2.1 Panel manufacturing

Robotic AFP equipment was used to manufacture 24-layer laminated panels nominally 1m by 1m in dimension at Electroimpact in Mukilteo, Washington. An eight lane AFP head with individual lane control for laser activation and output power deposited 6.35mm wide LM-PAEK™/AS4 carbon fiber thermoplastic tape at five different deposition rates (head traverse speeds): 0.085, 0.169, 0.339, 0.508, and 0.874m/s (200, 400, 800, 1200, 2000in/min). All panels were manufactured on an unheated aluminum table with a quasi-isotropic $[45, 90, -45, 0]_{3S}$ laminate schedule, with the first layer adhered to a Kapton film substrate which was secured to the table by vacuum and flash tape. Prior to manufacturing full size panels, four-ply calibration panels 0.3-0.4m square were used to determine appropriate laser power settings to achieve the target nip point temperatures for a given deposition rate. Figure 1 shows a completed full-size panel, with the Kapton film adhered to the aluminum tool. Flash tape is also visible at the edges of the panel, which was applied after the first four plies to help prevent warping and avoid the panel separating from the Kapton film during manufacturing. The first layer of each panel was deposited at 0.064m/s (150 in/min) to help ensure sufficient adherence to the Kapton layer, after which each subsequent was deposited at the target deposition rate.

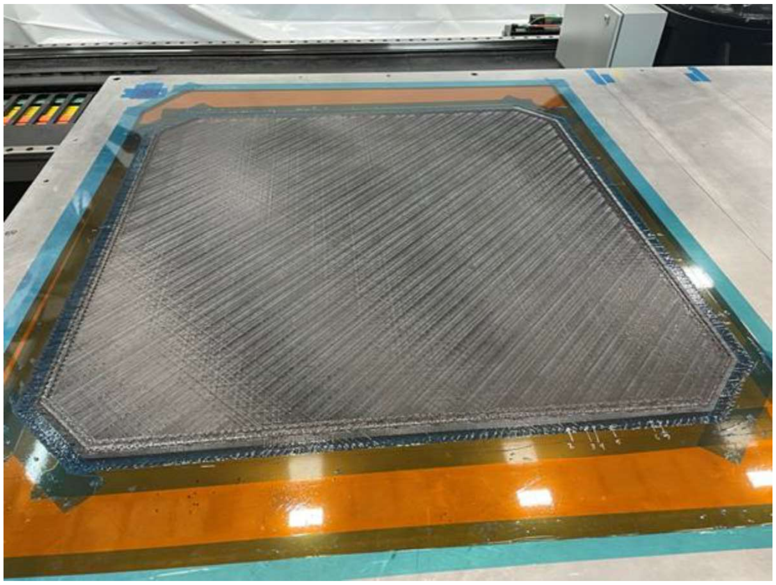

Figure 1 – Completed 24-layer LM-PAEK/AS4 panel on an aluminum layup table. Corners of the panel are omitted from manufacture due to minimum length requirements for fiber deposition. White spaces in the photo represent resin-rich areas on the panel surface. Dark areas correspond to the carbon fiber reinforcement.

All five deposition rates used a compaction force of 670N (150lbf) and a target nip point temperature of 375°C, except for the 0.847m/s rate. The calibration panel for the highest deposition rate (0.847m/s) indicated that there was not sufficient laser power available in the installed setup to achieve the target nip point temperature of 375°C, and that 310°C was the highest achievable temperature at that speed. The target temperature for the panel was accordingly reduced to 310°C, using the maximum 300W laser power available per lane. Table 1 summarizes the various configurations of laminates manufactured, including layup, deposition speed, and target nip point temperatures. A FLIR thermal imaging camera was used to monitor nip point temperature by taking real-time average temperatures across the width of the laser-heated region at the contact point between the roller and substrate to ensure appropriate laser power output levels.

Table 1 – Summary of AFP laminate manufacturing configurations

Material	Layup	Head Speed	Target Temperature
Victrex AE 250 LM-PAEK™/AS4 192gsm (FAW) 58% FVF	QI $[45/90/-45/0]_{3S}$	0.085m/s	375°C ± 15°C
		0.169m/s	375°C ± 15°C
		0.339m/s	375°C ± 15°C
		0.508m/s	375°C ± 15°C
		0.847m/s	310°C ± 25°C

2.2 Specimen preparation

All test specimens were cut from the panels using a high-pressure water jet, avoiding regions marked on the panels indicating potential defects, including tow splices, fiber-rich or resin-rich regions, split tows, etc. After cutting, test specimens were conditioned in a test laboratory at 23°C and 50% RH before being dimensioned with digital calipers. Specimens were then painted with flat white spray paint and speckled with flat black spray paint to create a stochastic pattern suitable for optical strain measurement. Tensile specimens were nominally 250mm in length and 25mm in width, and compressive specimens were nominally 1400mm in length and 13mm in width.

2.3 Experimental procedure

Tensile testing was conducted according to ASTM D3039 (*Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials*) [5] using an Instron 250kN electromechanical test frame with a constant crosshead displacement rate of 2mm/min. Full-field surface strains were measured using a GOM ARAMIS digital image correlation (DIC) non-contact optical strain measuring system. Applied force was captured coincidentally with each photo stage, which allows stress and strain values to be synchronized and tensile modulus and ultimate stress and strain properties to be computed. All testing was conducted in the same laboratory where specimens were conditioned prior to dimensioning, at 23°C and 50% RH. Figure 2 shows tensile specimens prepared for mechanical testing, with the white/black speckled region used for non-contact optical strain measurement.

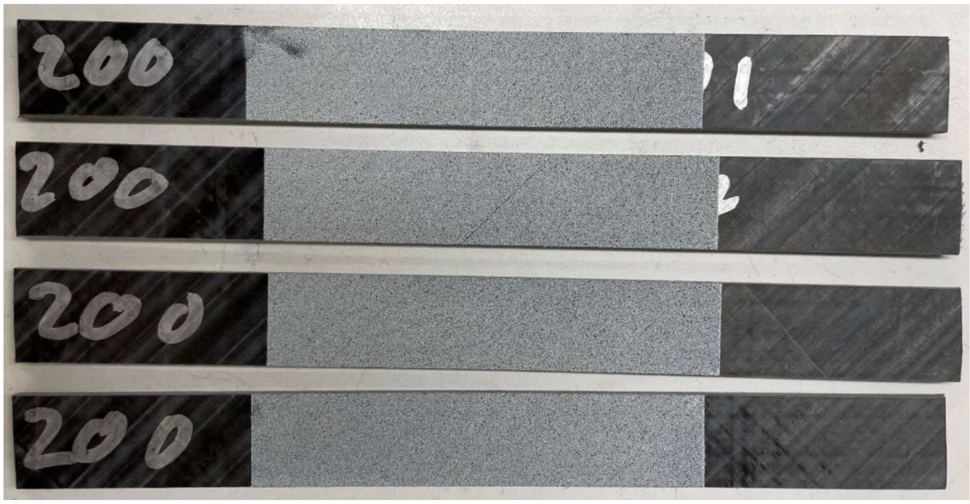

Figure 2 – ASTM D3039 tensile specimens with speckle pattern for DIC strain measurement

Compressive testing was conducting following ASTM D6641 (Standard Test Method for Compressive Properties of Polymer Matrix Composite Materials Using a Combined Loading Compression (CLC) Test Fixture) [6] using an Instron 100kN hydraulic test frame. Specimens were secured into a four-post combined loading compression fixture manufactured by Wyoming Test Fixtures and tested using a constant load head displacement rate of 1.3mm/min. Strain measurements were collected using the same DIC equipment and methods as used for tensile testing. Figure 3 shows a typical image from the DIC software at the beginning of a compressive test, with the specimen visible in the test fixture. The light blue region indicates the area over which strains are averaged to compute axial strains for calculating compressive modulus.

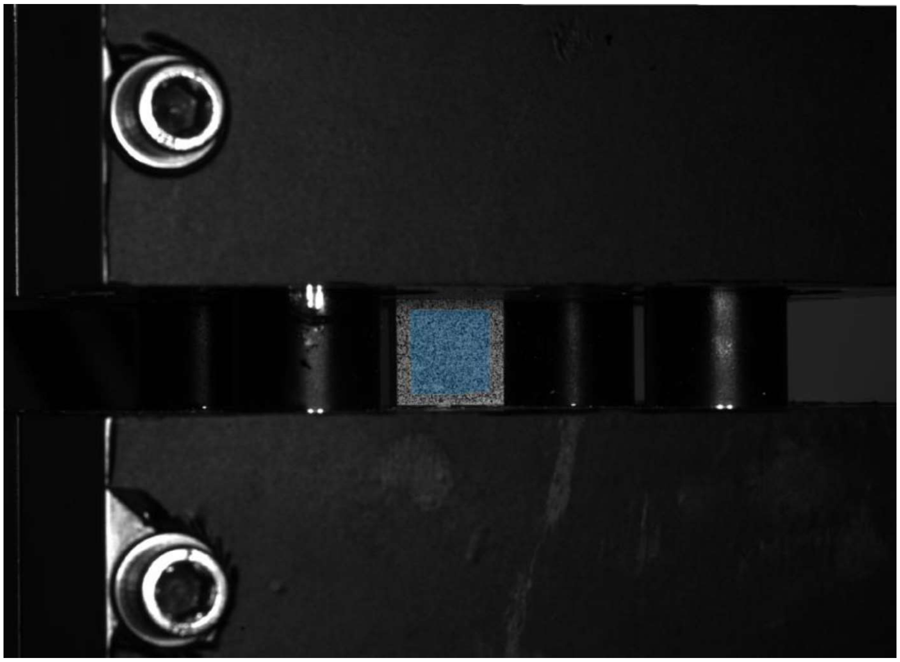

Figure 3 – Digital image correlation stage showing the compression specimen in the ASTM D6641 fixture. A light blue region centered on the speckled face of the gage region illustrates the region over which strain is averaged to compute axial strains

3. RESULTS

Of the five deposition rates included in the manufacturing portion of the study, the lower four rates (0.085m/s, 0.169m/s, 0.339m/s, 0.508m/s) achieved acceptable visual quality and consolidation to be included in the mechanical testing portion. The highest deposition rate (0.847m/s) had acceptable visual quality on first inspection, however the tows did not achieve sufficient consolidation and could be peeled apart by hand. Consequently, the full layup was not completed, and the panel was dropped from the mechanical test plan.

3.1 Tensile test results

Tensile properties exhibited coefficients of variation (COV) below 3.5% for all reported tensile strengths and tensile chord moduli (TCM), less than 5% COV for Poisson's ratio, and under 7% for strain to failure. When comparing to the "baseline" 0.085m/s panel, the 0.169m/s and 0.339m/s panels exhibited less than one standard deviation reduction in TCM, while the 0.508m/s showed a greater reduction, at 2.8 standard deviations.

Ultimate tensile strength showed greater variability between samples, with ultimate tensile strength (UTS) trending downward as deposition rates increased. In this case, UTS decreased by 2.60, 6.16, and 6.60 standard deviations from the baseline mean for 0.169m/s, 0.339m/s, and 0.508m/s, respectively. Figure 4 presents a graphical comparison of the TCM and UTS properties for each of the four deposition rates evaluated. Error bars indicate one standard deviation from the mean for each sample.

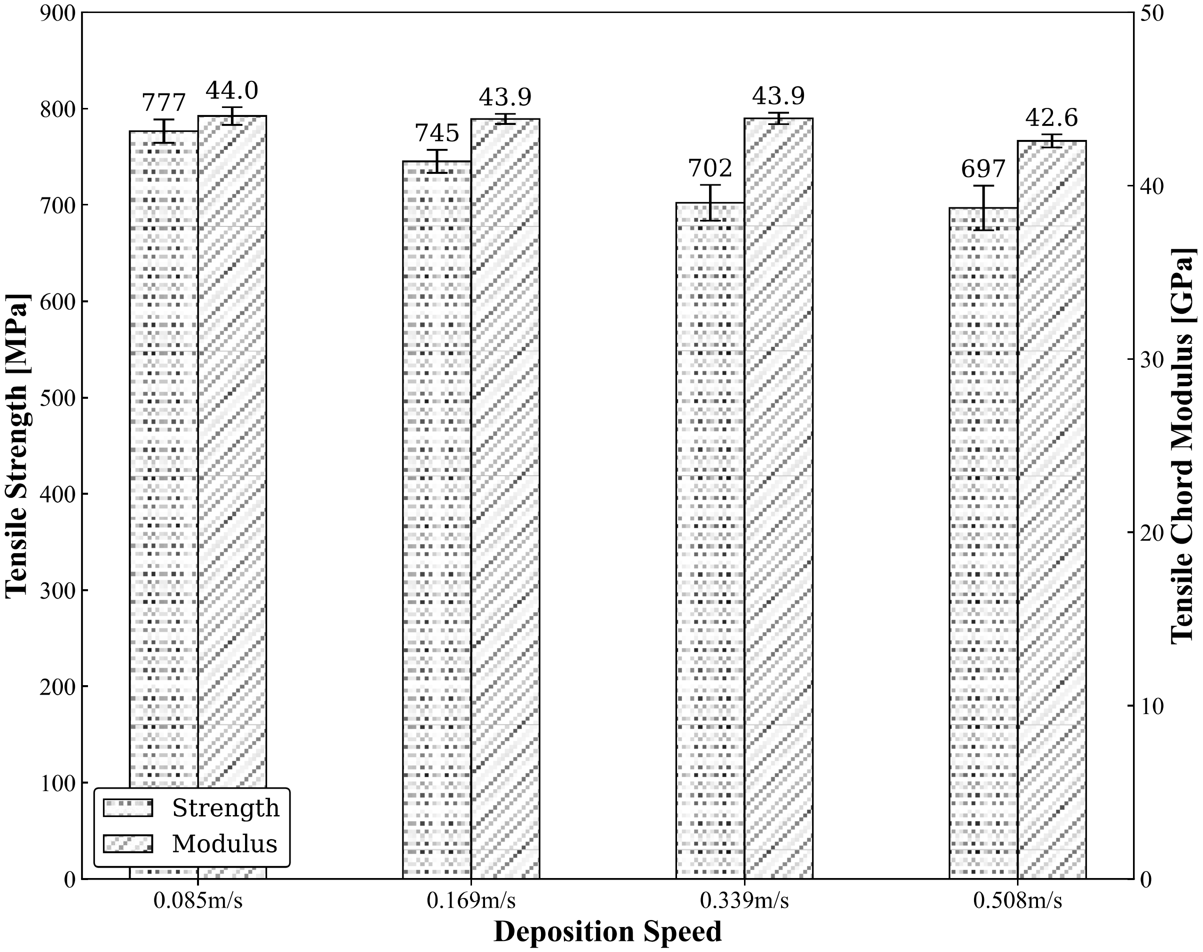

Figure 4 – Tensile strength and chord modulus for LM-PAEK™/AS4 AFP panels at various deposition rates

Tabulated results for each of the deposition rates are provided in Table 2, including tensile chord modulus, ultimate tensile strength, Poisson's ratio, and ultimate tensile strain. Poisson's ratio was consistent across all four deposition rates evaluated, while ultimate tensile strain decreased from 1.75% for the baseline panel as deposition rate increased. A slight return in strain to failure was seen for the fastest deposition rate, however this also coincided with slightly higher COVs for the 0.339m/s and 0.508m/s deposition rates than seen in the two lower deposition rates.

Table 2 – Summary of tensile properties for 24-layer LM-PAEK™/AS4 [45/90/-45/0]$_{3S}$ laminate at various deposition rates

Head Speed (n repeats)	Tensile Chord Modulus GPa / (COV)	Tensile Strength MPa / (COV)	Poisson's Ratio - / (COV)	Ultimate Tensile Strain - / (COV)
0.085m/s (7)	44.0 / (1.16%)	777 / (1.56%)	0.32 / (4.33%)	1.75% / (1.05%)
0.169m/s (6)	43.9 / (0.66%)	745 / (1.61%)	0.34 / (4.84%)	1.69% / (1.52%)
0.339m/s (6)	43.9 / (0.75%)	702 / (2.65%)	0.33 / (4.75%)	1.55% / (6.70%)
0.508m/s (6)	42.6 / (0.89%)	697 / (3.33%)	0.33 / (4.79%)	1.61% / (4.00%)
0.847m/s (6)	n/a	n/a	n/a	n/a

3.2 Compressive test results

Compressive properties within each sample exhibited under 3.5% COV for all four deposition rates evaluated for compressive modulus. Greater variability was seen between samples than observed for tensile testing, where comparing the increasing rates to the 0.085m/s baseline exhibited 2.0, 4.8, and 4.0 standard deviations from the baseline mean for the 0.169m/s, 0.339m/s, and 0.508m/s deposition rates, respectively.

Ultimate compressive strengths exhibited the greatest overall sensitivity to deposition rate compared to the baseline deposition rate. Significant reductions in compressive strength were observed as deposition rate increased, with 10.5, 20.1, and 21.1 standard deviation reductions observed for the 0.169m/s, 0.339m/s, and 0.508m/s laminates, respectively. These correlate to 12%, 23%, and 24% reductions in compressive strength compared to the baseline laminate. Figure 5 presents the compressive moduli and strengths for each of the four deposition rates evaluated, with error bars indicating one standard deviation from the mean for each sample. A tabulated summary of compressive moduli and strengths are provided in Table 3.

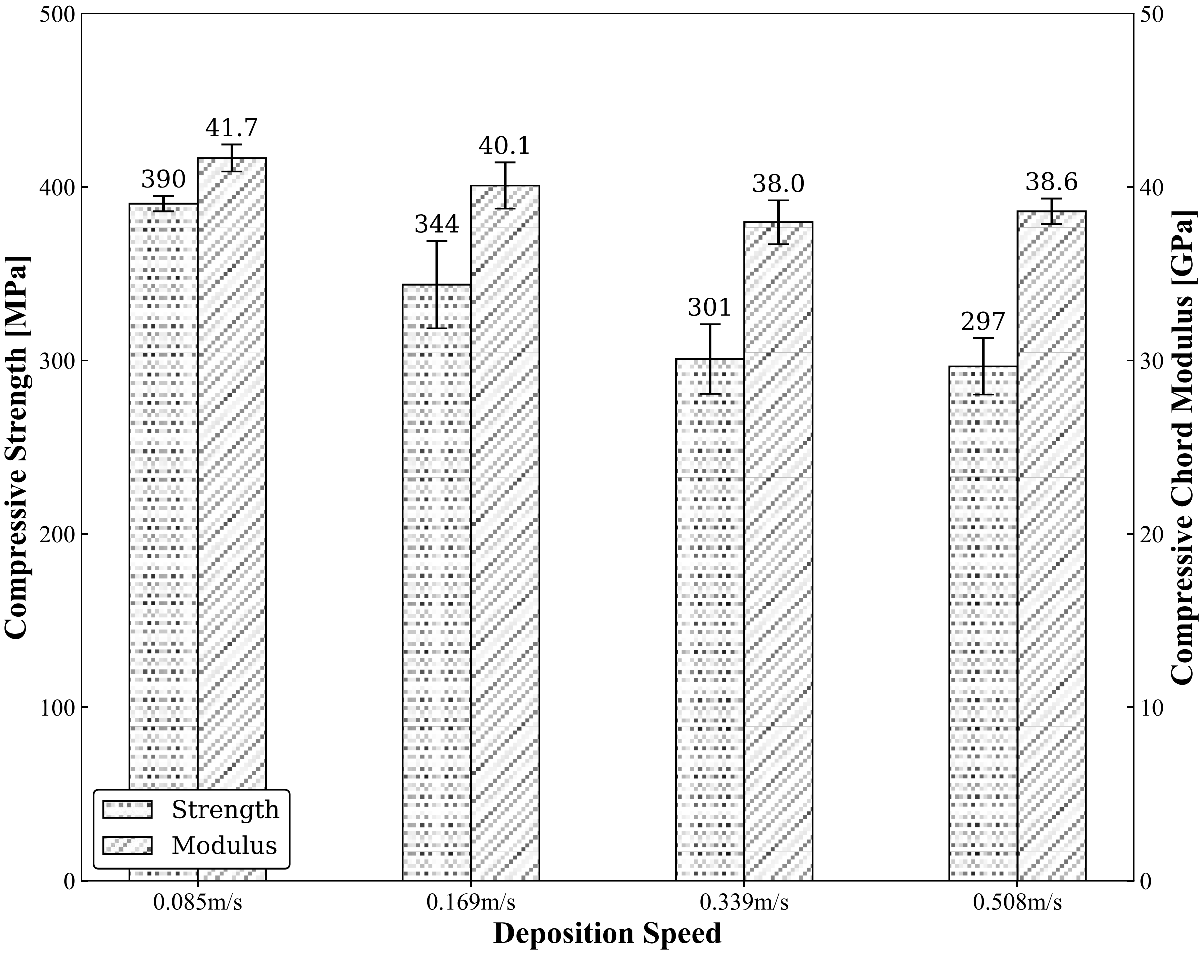

Figure 5 – Compressive strength and compressive modulus for LM-PAEK™/AS4 panels at various deposition rates

Table 3 – Summary of compressive properties for 24-layer LM-PAEK™/AS4 [45/90/-45/0]$_{3S}$ laminate at various deposition rates

Head Speed (n repeats)	**Compressive Modulus GPa / (COV)**	**Compressive Strength MPa / (COV)**
0.085m/s (5)	41.7 / (1.87%)	390 / (1.14%)
0.169m/s (5)	40.1 / (3.33%)	344 / (7.34%)
0.339m/s (5)	38.0 / (3.33%)	301 / (6.69%)
0.508m/s (5)	38.6 / (1.90%)	297 / (5.49%)
0.847m/s (5)	n/a	n/a

4. CONCLUSIONS

4.1 Manufacturing capabilities for in-situ consolidation

The mechanical performance of a high-performance carbon fiber reinforced thermoplastic tape has been evaluated under several different manufacturing conditions to better understand the deposition rate/performance relationship. It was observed that the material could be consolidated at rates higher than commonly found in the literature using in-situ consolidation [2, 3, 4], and equipment requirements have been bounded for higher deposition rates. More specifically, greater than 300W of laser power per lane is required to sufficiently melt and consolidate the LM-PAEK™ material when a post-consolidation stage is not part of the manufacturing plan. A target nip point temperature of 310°C was found to be insufficient for melting and consolidation at 0.508m/s when 300W laser power per lane was applied. A laser with higher output power could be installed on the robotic AFP equipment, but this was beyond the scope of this experimental study.

4.2 Effect of deposition rate on mechanical properties

4.2.1 Tensile properties

Laser-heated automated fiber placement was used to manufacture 24-layer laminated thermoplastic/carbon fiber panels to evaluate the effect of deposition rate on tensile and compressive behavior. Tensile strength trended downward as deposition rate increased, dropping 4.0% from the baseline rate (at 0.085m/s) for the 0.169m/s panel, 9.6% from the baseline for the 0.339m/s panel, and 10.3% for the 0.508m/s panel. Tensile chord modulus was consistent across the first three rates with less than 0.4% decrease, and with a slightly larger 3.3% decrease at the highest rate.

4.2.2 Compressive properties

Compressive mechanical properties exhibited similar behavior, though to a more significant extent than tensile properties. Compressive strengths were reduced by 12%, 23%, and 24% for the 0.169m/s panel, 0.339m/s panel, and the 0.508m/s panel, respectively, again showing a plateau at the highest deposition rate. Compressive moduli reduced by 3.8%, 8.9%, and 7.4% from the baseline for the three increased rates.

4.2.3 Deposition rate vs. mechanical performance

With the expensive infrastructure typically associated with the implementation of automated fiber placement for structural components, such manufacturing methods have not been widely adopted in industries beyond aerospace applications. While there is a degradation in tensile and compressive properties at higher deposition rates, a 10% penalty for tensile strength and 24% for compressive strength may be an acceptable trade when the deposition rate is increased six-fold for applications where throughput is highly valued, and structures are less weight-critical than commonly seen in aerospace. This, combined with a potential to eliminate the need for costly equipment such as ovens and autoclaves, may enable more cost-competitive solutions in new industries such as marine applications.

5. REFERENCES

1. Dirk, H-JA Lukaszewicz, Carwyn Ward, and Kevin D. Potter. *The engineering aspects of automated prepreg layup: History, present and future.* Composites Part B: Engineering 43.3, 2012. DOI: doi.org/10.1016/j.compositesb.2011.12.003
2. Heathman, Nathaniel, et al. *In situ consolidation of carbon fiber PAEK via laser-assisted automated fiber placement.* Composites Part B: Engineering 249, 2023. DOI: doi.org/10.1016/j.compositesb.2022.110405
3. Raps, Lukas, et al. *CF/LM-PAEK: Characterisation and sensitivity to critical process parameters for automated fibre placement*. Composite Structures 284, 2022. DOI: doi.org/10.1016/j.compstruct.2021.115087
4. Raps, Lukas, et al. *High speed processing of low-melt Polyarylether-ketone Prepreg using in-situ consolidation Automated Fiber Placement*. SAMPE Conference Proceedings, 2023.
5. ASTM Standard D3039, *Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials*, ASTM International, West Conshohocken, PA, 2017. DOI: 10.1520/D3039_D3039M-17.
6. ASTM Standard D6641, *Standard Test Method for Compressive Properties of Polymer Matrix Composite Materials Using a Combined Loading Compression (CLC) Test Fixture*, ASTM International, West Conshohocken, PA, 2017. DOI: 10.1520/D6641_D6641M-16E02.