

Multi-Stage Consolidation Strategy to Improve Impregnation Quality in Thermoplastic UD Tapes

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Abstract. Incomplete impregnation is a remaining challenge in the production of thermoplastic unidirectional (UD) tapes, particularly for the melt impregnation. This study investigates an approach analogous to multi-stage die impregnation by re-calendering partially impregnated UD thermoplastic tapes, where different closing forces under controlled processing conditions are used to enhance impregnation quality. In this work, polypropylene–carbon fiber (PP-CF) tapes with a width of 20 mm and a thickness of 400 µm were produced by using an Xplore UD Tape Line with a closed pultrusion die. As a model sample, these tapes were deliberately produced under conditions expected to result in partial impregnation by setting the die pressure and pultrusion rate accordingly. To improve impregnation, the tapes were subsequently subjected to calendaring with different nip force passes in a different line, thereby mimicking a staged or multi-die consolidation approach. Results show that calendaring induces pronounced geometric reconfiguration accompanied by improved impregnation quality. Tape thickness was reduced by up to approximately 65%, while tape width increased by up to approximately 70%, indicating effective lateral spreading under compressive and shear stresses. Optical microscopy of polished cross-sections revealed a reduction of dry fibre regions and improved resin continuity within inter-filament gaps at intermediate calendaring nip force. Density-based fiber volume fraction of the tape measurements showed only a slight increase in the range of 2–3%, suggesting that consolidation was governed primarily by fibre rearrangement and spreading rather than significant resin squeeze-out. The findings provide practical insights into how the calendaring unit of a thermoplastic tape manufacturing line can be adapted for multi-stage consolidation, offering improved impregnation quality in thicker thermoplastic tapes that are more prone to impregnation defects. This approach may also serve as a bridge solution when the pressure build-up is limited.

Introduction

Thermoplastic unidirectional (UD) tapes are increasingly adopted in automated composite manufacturing because of their recyclability, rapid processing capability, and suitability for out-of-autoclave consolidation [1-3]. Their performance, however, is governed by the degree of impregnation achieved during production. In thermoplastic extrusion-based impregnation processes (TPR), the molten polymer must penetrate tightly packed fibre bundles or spread tows, yet the high melt viscosity of thermoplastics and the limited pressure build-up inside the die often lead to partially impregnated regions and persistent micro-voids [4, 5]. Achieving consistent impregnation is particularly challenging for thermoplastic tapes produced via TPR, where resin viscosity, insufficient pressure generation in the closed die, and incomplete tow spreading restrict resin mobility and capillary flow within the fibre bundle [6, 7].

The Delft TapeLab is a unique open research facility for unidirectional thermoplastic tapes and their applications, where it facilitates research-scale (UD Tape line, Xplore Instruments, the Netherlands) and semi-industrial unidirectional tape manufacturing line (Van Wees, the Netherlands). The Xplore

UD Tape line consists of a benchtop microcompounder (MC15HT) attached to a benchtop UD Tape line consisting of a de-winding unit, spreaders, pultrusion die, and take-up winders. The semi-industrial unidirectional tape manufacturing line includes a creel cabinet for continuous fibre feeding, a heated main roll where polymer and fibres are combined, calender rolls for pressing and shaping the composite into a tape, and cooled rolls for stabilising and winding the product. The line also offers three interchangeable impregnation routes: thermoplastic extrusion impregnation (TPR), where the extruded melt is deposited onto fibres on a heated roller; kiss-roll impregnation (DPR), where fibres pick up polymer dispersion from a bath before water evaporation and melting on the main roller; and nip-roll impregnation (NPR), where fibres are introduced horizontally between rolls that both transfer polymer dispersion, followed by drying and melting.

Improving impregnation within the constraints of existing equipment remains a critical objective for both research-scale and industrial tape manufacturing. A more flexible strategy is to exploit consolidation units already present in most thermoplastic tapelines. Within this system, the calendaring unit plays a crucial role. It applies localized compressive and shear stresses to the molten or semi-molten tape, promoting resin mobility and facilitating penetration into micro-scale inter-fibre gaps [8, 9]. When applied in different stages, calendaring can emulate a multi-die impregnation strategy by providing repeated opportunities for void elimination and resin redistribution without requiring the die to produce an impregnated tape. A limitation in using calendaring as a consolidation tool is the narrow processing window. Excessive pressure can distort fibre architecture, cause non-uniform tow spreading, or squeeze out resin, unintentionally altering the fibre volume fraction. Insufficient temperature, on the other hand, reduces resin mobility and makes additional passes ineffective. Detailed insight into how parameters such as roll temperature, nip force, and pass count affect microstructural evolution is, therefore, essential for determining when calendaring improves impregnation. Despite this potential, the effect of calendaring on thermoplastic tape impregnation quality has not been systematically explored, particularly for narrow tapes with severe pressure gradients. At present no clear framework exists describing how calendaring influences filament packing, resin distribution, void content, and the evolution of tape geometry.

In this study, we investigated whether the calendaring unit can be used as a controlled multi-stage consolidation method to enhance impregnation quality in partially impregnated thermoplastic UD tapes. For this purpose, a modular Xplore UD Tape Line was employed to investigate the role of downstream consolidation on the impregnation quality of thermoplastic unidirectional (UD) tapes. The system enables the production of UD tapes with tailored width, thickness, and fibre volume fraction (V_f), allowing flexible adaptation to material systems and application-driven requirements. By optimizing the parameters, a fully impregnated carbon fiber-based UD tape can be obtained by using this lab-scale line. A representative tape, produced using a die with 12.7 mm width and an exit thickness of 170 μm , employing 24K carbon fibre tows (DowAksa) and polypropylene (SABIC PP 519A), is shown in Figure 1. This representative micrograph of the tape illustrates the achievable tape uniformity and impregnation state with a calculated volume fraction of 49,12%.

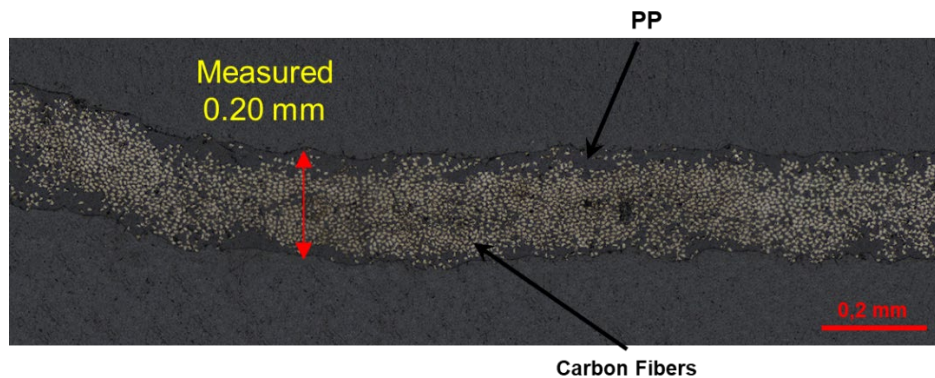


Fig. 1. Micrograph for a representative CF/PP tape produced with Xplore UD Tape Line (Die temperature of 225 °C, and line speed of 0.3 m/min.).

In this study, polypropylene–carbon fibre (PP–CF) tapes with a width of 20 mm and an initial thickness of 400 μm were manufactured using an Xplore UD Tape Line with a die under conditions deliberately selected to yield partial impregnation. These tapes were subsequently processed on a separate tape manufacturing line where multiple calendaring passes were applied under well-defined temperatures and different closing forces of the belts. Tape quality after each calendaring stage was characterized through optical microscopy of polished cross-sections and quantitative image analysis to assess voids. Thickness, width, and areal weight were monitored to quantify geometric evolution, while density measurements provided estimates of fibre volume fraction and void content. Together, these results enabled the identification of processing conditions where impregnation is improved without inducing undesirable changes in dimensional stability or fibre architecture.

2. Materials

The materials used in this study consisted of T800SC-10E-24K carbon fibres supplied by TORAY and Polypropylene SABIC PP 519A, a homopolymer grade with a melt flow index of 35 g/10 min (230 $^{\circ}\text{C}$ /2.16 kg). The polymer and fibres were processed in continuous form without any pre-impregnated intermediates. The PP pellets were dried at 80 $^{\circ}\text{C}$ for 4 h prior to use to minimise moisture during melt impregnation.

3. Experimental Campaign

3.1. Narrow Tape Production with Xplore UD Tape Line

The initial stage of tape manufacturing was carried out using an Xplore 15 cc micro-compounder (MC15HT, Xplore Instruments, the Netherlands) in combination with the Xplore UD Tape Line (Figure 2), which is equipped with a spreading unit, melt impregnation die, pulling and winding unit. T800SC-10E-24K carbon-fiber rovings were guided through the melt impregnation die, where molten polypropylene (PP) was introduced into the die at a processing temperature of 225 $^{\circ}\text{C}$. With the help of the continuous feeders on MC15HT, the feed rate of PP was kept constant. A die exit geometry with 20 mm width and a thickness of 400 μm was utilized. Two manufacturing configurations were investigated at this stage, differing in the number of rovings fed into the die, as 2x24K and 4x24K rovings. The theoretical volume fraction is the ideal situation for filling the die without any gaps. The resulting fibre volume fractions (V_f) of the as-produced tapes were measured as 28.52 % for Rov2-XP and 37.52 % for Rov4-XP (Table 1). One should note that the UD tapes were deliberately produced partially impregnated by adjusting the line speed and die pressure accordingly. Both configurations exhibited pronounced dry regions and non-impregnated fibre regions, indicating insufficient pressure build-up within the closed die during melt impregnation. These partially impregnated (as-produced) tapes were therefore used as baseline material for the subsequent consolidation step.

Table 1. Process parameters used to manufacture tapes at the Xplore setup.

Number of Roving	Sample Code	Pulling Speed (m/min)	Die Temp ($^{\circ}\text{C}$)	Theoretical V_f (%)	Calculated V_f (%)
2	Rov2-XP	0.5	225	14.30	28.52
4	Rov4-XP	0.5	225	28.61	37.52

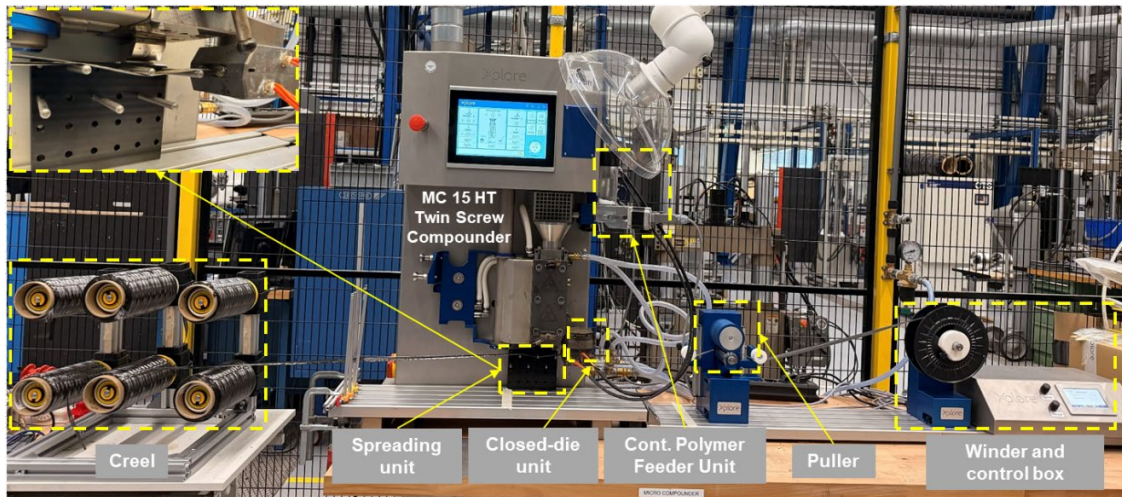


Fig. 2. Xplore's UD tape line with an interchangeable number of roving creel setup and closeup image of the spreading and die units.

3.2. Calendaring Stage with Semi-industrial Tapeline

The second stage of processing was performed on a UD thermoplastic tape manufacturing line, focusing on the calendaring unit (Figure 3).

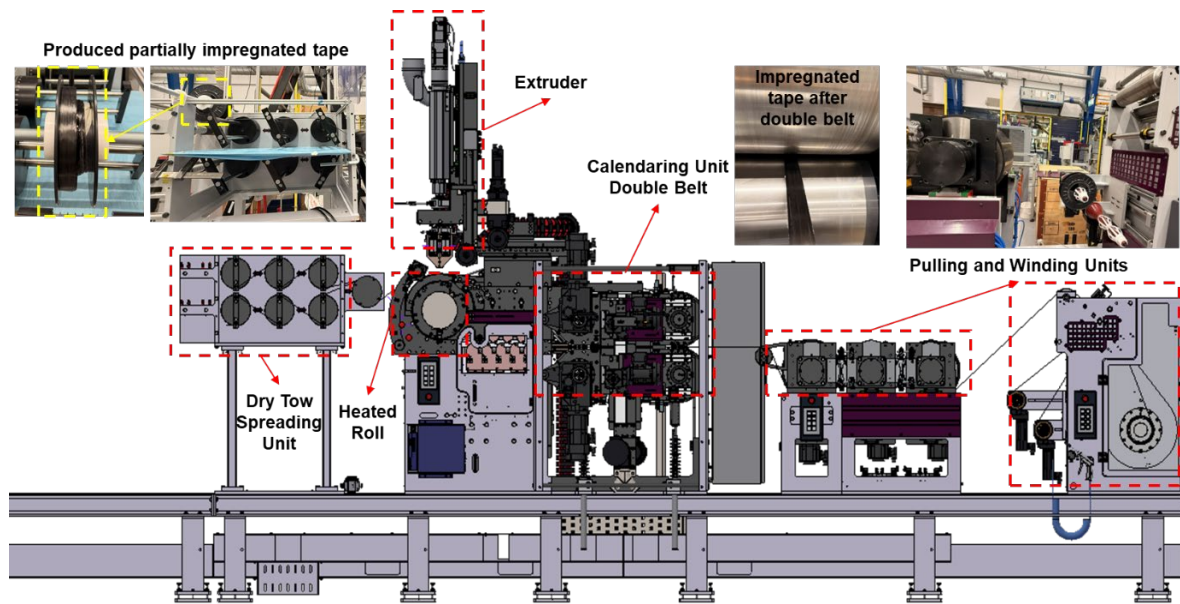


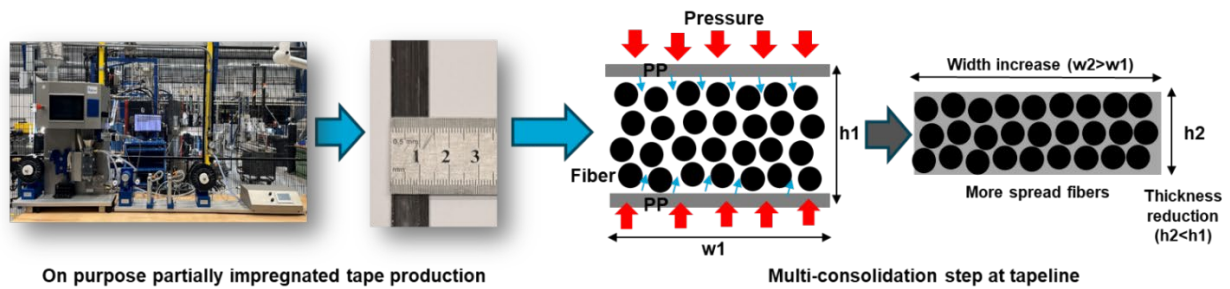
Fig. 3. Semi-Industrial UD thermoplastic tape manufacturing line and calendaring stage of partially impregnated tapes.

In this stage, the produced partially impregnated baseline tapes were processed through a line equipped with a calendar and double-belt system to enhance consolidation and impregnation. The calendaring unit functioned as a controlled consolidation zone, allowing independent adjustment of nip force and roll temperature. Each calendaring condition applied a defined nip load while maintaining the roll temperature at 220°C , matching the die temperature used during the initial Xplore processing in order to preserve comparable melt viscosity and flow behavior. Following each calendaring pass, the tape exited the belt and cooled under ambient conditions. No additional tension was applied beyond the standard feeding tension of the line, ensuring that any observed changes in tape geometry were solely attributable to the calendaring process. For each baseline configuration (Rov2-XP and Rov4-XP), three progressively increasing nip forces were investigated: 500 N, 1000 N, and 1500 N (Table 2).

Table 2. Process parameters used to calendar tapes at the semi-industrial tapeline.

Sample code	Nip (Closing) Force (N)	Pulling Speed (m/min)
Rov2-500, Rov4-500	500	1.0
Rov2-1000, Rov4-1000	1000	1.0
Rov2-1500, Rov4-1500	1500	1.0

The pulling speed was maintained at 1 m/min, which is lower than typical industrial production rates but was deliberately selected to allow detailed investigation of impregnation and fibre spreading behavior during secondary consolidation. The complete schematic of the multi-stage consolidation approach, spanning from the Xplore system to the semi-industrial tape manufacturing line, is presented in Figure 4.

**Fig. 4.** Schematic of the multi-stage consolidation approach.

4. Characterization Steps

Various characterization techniques were employed to evaluate the influence of the calendaring processes on the spreading and quality of CF/PP tapes. The applied methods included geometrical measurements, volume fraction analysis by weighing, and optical microscopy.

Geometrical characterization was conducted to quantify changes in tape dimensions induced by spreading at the calendaring stage. The width and thickness of the CF/PP tapes were measured after spreading and compared with the as-produced reference tapes from Xplore tapeline (0% spreading). For each tape condition, at least 10 measurements of maximum width and maximum thickness were taken at intervals of 20 cm along a total tape length of 2 m to capture longitudinal variability. Tape width was measured using a Mitutoyo Series 500 vernier caliper with a resolution of 0.01 mm, while thickness measurements were performed using a Mitutoyo Series 293 micrometer with a resolution of 0.001 mm. Based on these measurements, the cross-sectional area (CSA) was calculated to assess whether the spreading process altered the tape geometry. The fiber volume fraction of the tapes was determined by weighing a 1-meter specimen and applying the known densities of the carbon fiber (1.8 g/cm^3) and polypropylene resin (0.9 g/cm^3), thereby accounting for any resin loss resulting from squeeze-out during the calendaring process.

For microstructural analysis, samples were extracted from both Xplore-produced and calendered tapes, embedded in epoxy, and subsequently ground and polished in an automated polishing machine (Struers Tegramin-30) to obtain high-quality cross-sections. A Keyence VK-X1000 confocal laser scanning microscope was used to investigate the effect of spreading on fibre distribution, resin, and the presence of dry regions or voids. Three samples were analyzed for each condition, covering eight sample groups: non-calendered Xplore tapes produced with 2 and 4 rovings, and tapes calendered under 500 N, 1000 N, and 1500 N. Image processing techniques were applied to the acquired micrographs to see the changes in tape composition, including fibre/resin-rich areas and void regions.

5. Results and Discussions

5.1. Geometrical Measurements

Geometrical measurements are shown in Figure 5, which gives a clear response of CF/PP tapes after the calendaring process.

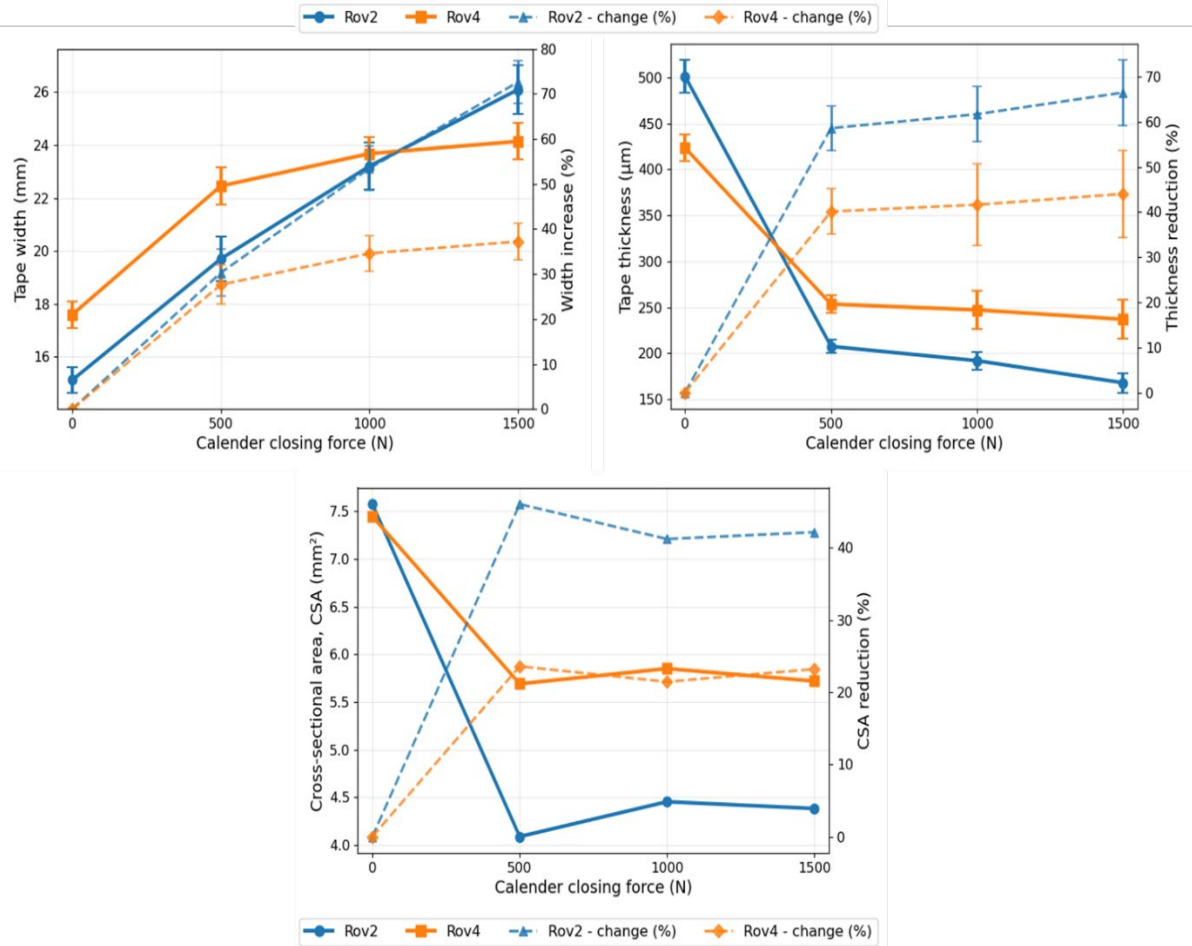


Fig. 5. Changes with calendar nip force vs. (a) Tape width, (b) Tape thickness, (c) Cross-sectional area.

Calendaring induced a geometrical reconfiguration of the tapes, characterized primarily by thickness reduction and lateral spreading, while only marginally affecting the fibre volume fraction. For the Rov2 configuration, increasing calendar nip force from the as-produced state to 1500 N led to a reduction in average thickness from $\sim 501 \mu\text{m}$ to $\sim 168 \mu\text{m}$, corresponding to a thickness reduction of approximately 66%. In parallel, the tape width increased substantially from 15.1 mm to 28.1 mm, representing a $\sim 73\%$ width increase (Figure 6). The calculated cross-sectional area (CSA) decreased from 7.58 mm^2 to $\sim 4.38 \text{ mm}^2$ with increasing calendaring force. As the CSA was derived from nominal width and locally measured thickness, the absolute values are influenced by surface roughness and thickness non-uniformity. Therefore, the observed reduction reflects profile homogenisation and compaction during calendaring. A similar but less pronounced trend was observed for the Rov4 configuration, where the higher initial fibre content constrained deformation. The tape thickness decreased from $423 \mu\text{m}$ to $237 \mu\text{m}$ at 1500 N, corresponding to a thickness reduction of approximately 44%, while the width increased from 17.6 mm to 24.1 mm ($\sim 37\%$ increase). CSA decreased from 7.45 mm^2 to $\sim 5.72 \text{ mm}^2$, showing a more moderate consolidation response compared to Rov2.

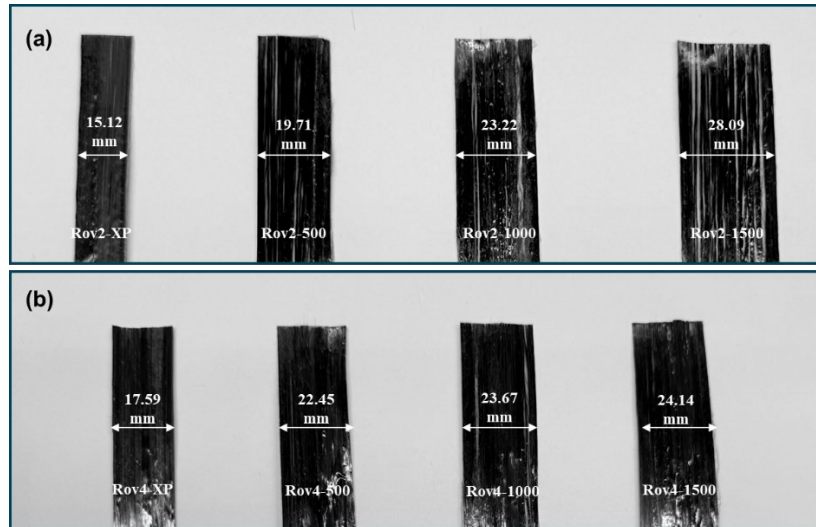


Fig. 6. The width difference of (a) number of 2 (b) number of 4 roving produced tapes.

Despite significant thickness reduction and lateral widening of the tapes during calendaring, the fibre volume fraction increased only slightly (from 28.5% to ~31.9% for two-rovings tapes, and from 37.5% to 39.2% for four-rovings tapes, Table 3). This suggests that the main effect of calendaring is fibre rearrangement and tow spreading, rather than substantial resin squeeze-out, which would have led to a larger increase in Vf.

Table 3. Measured fiber volume fraction and resin loss at different calendaring forces.

Calendaring Force (N)	Rov2 Vf (%)	Rov2 Resin Loss (%)	Rov4 Vf (%)	Rov4 Resin Loss (%)
0 (XP)	28.52	-	37.52	-
500	30.13	7.47	38.12	2.51
1000	31.55	13.43	38.48	3.98
1500	31.87	14.70	39.15	6.67

Clancy et al. investigated in-line spreading of CF/PEEK pre-preg tapes using a dedicated spreading device integrated into an LAMP head, where tape width was increased by applying pressure and heat close to the melt temperature of PEEK [10]. Their results showed that increasing applied pressure led to a systematic increase in tape width and a corresponding decrease in thickness, while the cross-sectional area and fibre volume fraction remained approximately constant across spreading levels up to ~62% width increase. This behaviour was attributed to transverse squeeze flow, where the viscous thermoplastic matrix enables lateral redistribution of fibres under compression without significant resin loss [10, 11].

5.2. Confocal Microscopy

Figure 7 presents representative polished cross-sections of partially impregnated as-is tapes (Rov2-XP and Rov4-XP) and the same tapes after secondary calendaring at increasing nip forces of 500, 1000, and 1500 N. The as-is UD tapes exhibit clear evidence of incomplete impregnation, characterized by localized resin-rich regions, dry fiber bundles, and non-uniform filament packing. These features are particularly pronounced for the Rov2-XP configuration, where limited pressure build-up during melt impregnation restricts resin penetration into inter-filament gaps. The partially impregnated Rov2 and Rov4 tapes exhibit non-planar geometry, irregular thickness profiles, and extended dry fibre regions. In these areas, the contrast between dry fibre bundles and the embedding resin is insufficient for reliable threshold-based segmentation, leading to significant uncertainty in automated void quantification. For this reason, void evolution is discussed qualitatively in the present work, supported by mass-per-length measurements and fibre volume fraction data. Following secondary calendaring, a clear nip force-dependent evolution of tape geometry and microstructure is observed. At 500 N, both Rov2 and Rov4 tapes show a substantial reduction in thickness accompanied by an increase in tape width, indicating the onset of lateral spreading under compressive and shear

stresses imposed by the calender rolls. Microstructurally, this stage promotes improved filament rearrangement and partial filling of inter-bundle voids, although residual dry regions remain visible, especially in the Rov2 configuration. At 1000 N, calendaring produces the most homogeneous spreading response for both Rov2 and Rov4. The tape width increases further while the thickness is reduced in a controlled manner, leading to a more uniform filament distribution across the tape cross-section. Micrographs reveal enhanced resin continuity along the fiber bed, reduced clustering of dry filaments, and a smoother impregnation front. This nip force level appears to provide sufficient resin mobility to promote filament-level rearrangement without inducing excessive resin displacement. The improved spreading at this stage is consistent with the measured geometric trends, where width increase and thickness reduction occur concurrently while the overall cross-sectional area remains relatively stable. Increasing the nip force to 1500 N results in diminishing returns and the onset of adverse effects, particularly for the Rov2 tapes. Although further width increase and thickness reduction are observed, microstructural inspection reveals localized fiber splitting, increased surface roughness, and the re-emergence of dry fiber regions, especially for Rov4 sample. These features are indicative of resin squeeze-out and non-uniform pressure transmission through the fiber bed, leading to localized resin depletion rather than further impregnation improvement. In the Rov4 configuration, the higher initial fiber content provides greater resistance to excessive spreading, yet signs of resin redistribution and localized heterogeneity are still evident at the highest calendaring nip force.

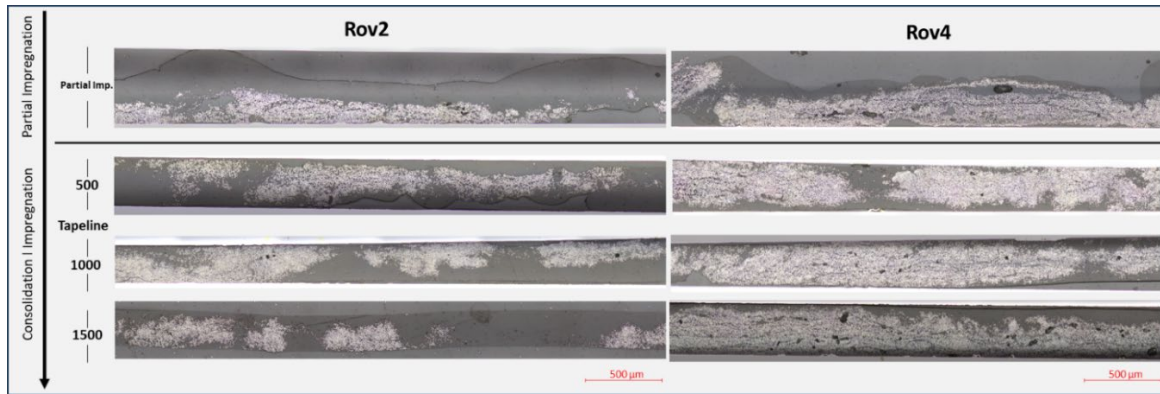


Fig. 7. Micrographs for the CF/PP tape produced in the current study.

6. Conclusion

This study demonstrates that secondary calendaring can be used as a multi-stage consolidation strategy to enhance the microstructural homogeneity of partially impregnated PP–CF UD tapes. Increasing calendaring pressure induced pronounced thickness reduction and lateral spreading, with thickness reductions of up to ~66% (Rov2) and ~44% (Rov4), accompanied by width increases of ~73% and ~37%, respectively.

Qualitative examination of the cross-sections indicates a visible reduction in void regions after calendaring. However, due to the geometric irregularity and surface roughness of Rov2_XP and Rov4_XP tapes, quantitative void content analysis from micrographs was not considered sufficiently reliable. The observed increase in fibre volume fraction and measured resin loss further support the occurrence of densification and matrix redistribution during calendaring.

Microstructural observations showed that intermediate pressure (1000 N) provided the most homogeneous fibre distribution and resin continuity, while higher nip force (1500 N) led to fibre splitting and local resin loss. Despite significant geometric changes, fibre volume fraction increased only marginally (3–4%), indicating that consolidation was dominated by fibre rearrangement rather than resin squeeze-out.

The tapes studied are intentionally thick and narrow, representing a challenging impregnation case where pressure build-up is limited. The results are therefore mostly applicable to such geometries. For thinner and wider tapes, transverse flow during calendaring is expected to be more constrained;

however, the findings may still remain relevant in demonstrating how multi-stage pressure application enhances microscale impregnation, even when full transverse flow is limited.

Overall, an optimum processing window was identified where impregnation quality is enhanced without compromising tape integrity. Future work will investigate microstructural in-depth analysis, laminate-level mechanical performance, and crystallization morphology to assess the structural implications of multi-stage consolidation.

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