



Fibre waviness reduction in thermoplastic pultrusion by using DREF yarns

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ABSTRACT

Non-reactive thermoplastic pultrusion impregnation issues are mitigated by using hybrid input materials. Co-wound (CW) and commingled yarns are an assembly of continuous polymer and reinforcement fibres. Continuous thermoplastic fibres have shown to induce waviness in the reinforcement fibres during pultrusion due to their shrinkage at high temperature. DREF yarns are composed of a core of continuous reinforcement fibres onto which discontinuous polymer fibres are applied using the friction spinning process. This study, based on the application of 3 N and 0 N tension on CW and DREF yarns, aimed to highlight the contribution of discontinuous polymer fibres on reducing reinforcement waviness in pultruded rods. CW yarns' reaction to heating showed continuous polyethylene terephthalate (PET) fibres shrinkage resulting in wavy glass fibres (GF). Conversely, the GF in DREF yarns remained straight. Pultrusion experiments with yarn tension of 3 N were done to alleviate the GF waviness. However, the porosity was rather high at 4.2 % for CW rods and 2.3 % for DREF rods. Pultrusion experiments without tension showed lower porosity of level of 2.9 % for CW yarns and as low as 1.1 % for DREF yarns. However, CT-scan image indicated GF waviness in CW rods. GF in DREF rods remained straight. The in-plane shear strength reached 119 MPa. Thermoplastic pultrusion using DREF yarns resulted in composites without reinforcement fibre waviness, lower porosity level and superior shear strength.

1. Introduction

The increasing adoption of thermoplastic composites in various industries can be attributed to their numerous advantages over thermoset composites [1,2]. These advantages include high impact resistance and enhanced fracture toughness [1–3]. Additionally, their post-forming, re-shaping, and recycling ability makes them preferred replacements for metallic and traditional thermoset parts in sectors like automotive, aerospace, and marine industries [4,5]. Environmental concerns about waste management are increasing due to the recycling challenges posed by thermoset composites. These materials often end up in landfills, highlighting the need for better material alternatives, like thermoplastics [4,5]. However, their production and usage remains under development due to inherent challenges, primarily the high viscosity of thermoplastic polymers resulting in impregnation issues, especially in cost-sensitive applications [4,6,7].

The pultrusion process enables the production of products with a constant cross-section that can achieve a high fibre volume fraction [8]. This manufacturing process is highly efficient due to the little need for operator intervention [8]. Pultruded products exhibit excellent

mechanical, chemical, and structural properties, and find applications across various industries [9]. Continuous pultrusion of fibre-reinforced composites with thermoset matrix is a well-established and widely used manufacturing method, compared to thermoplastic matrix pultrusion [1]. Due to the advantages offered by thermoplastic materials, thermoplastic pultrusion has gained popularity over the past 50 years through the usage of different technologies and input materials [1,10].

The drawback in thermoplastic pultrusion is related to the impregnation challenges due to their molten viscosity being 10 orders of magnitude higher than thermosets polymer [11]. To try to compensate for the high viscosity of thermoplastics, several pultrusion techniques and input materials have been developed. The term 'input material' refers to a range of material formats used for pultrusion manufacturing. This includes reinforcement fibres, such as carbon or glass, polymer pellets, prepreps, and hybrid yarns. Similar techniques to those used in thermoset pultrusion, such as thermoplastic injection pultrusion [12], and reactive thermoplastic pultrusion [13] are employed. For these techniques, dry reinforcement yarns are fed into the pultrusion die separately from the polymer. In thermoplastic injection pultrusion, melted thermoplastic pellets are injected into the die where the

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impregnation takes place. This technique is limited to small cross-section pultrudates such as tapes or otherwise using less available thermoplastic polymers engineered with low viscosity [1,12]. In reactive thermoplastic pultrusion, low viscosity monomers are injected in the die, enabling easy impregnation. This process is limited to specific polymers and requires consequential process control. Another approach is to use hybrid yarns as input materials, where the polymer is integrated to the reinforcement yarn. The idea is to reduce the distance that the polymer must travel to impregnate the reinforcement fibres. Such examples of input materials are called prepregs, towpregs, commingled, co-wound (CW) and DREF yarns. Prepregs are thin pre-impregnated tapes that are comprised of fully impregnated reinforcement fibres with a thermoplastic polymer, resulting in a relatively rigid form and are typically expensive [14]. Commingled yarns consist of reinforcement fibres that are mechanically mixed with continuous polymer fibres. Mixing techniques usually involve passing the fibres through air-jet channels [15,16]. These yarns are typically more expensive than the ones that follow. Towpregs are made by mixing powdered polymer to the reinforcement tows [17]. CW yarns are composed of reinforcement tows and thermoplastic polymer tows arranged side by side. The assembly of these CW yarns does not require any mixing technique. To ensure their integrity, these yarns are sometimes twisted [18,19]. In the nineteen seventies, Ernst Fehrer developed and commercialised a friction spinning system for textiles under the name DREF [20]. DREF yarns are composed of continuous reinforcement fibre core onto which discontinuous polymer fibres are spun [20]. To the authors' knowledge, DREF yarns were never used as input materials in thermoplastic pultrusion.

During hybrid yarn input material thermoplastic pultrusion, input materials are wound into bobbins which are positioned in a creel. The creel is used to hold the bobbins and to regulate their unwinding tension [18]. These yarns are then drawn through a preheater, a heated die, and a cooling system using a puller mechanism. At the end of the manufacturing line, a saw is employed to cut the finished products. The crucial stage of melting and impregnation occurs within the heated die. This die is typically configured with a tapered section to create impregnation pressure, followed by a short constant section for shaping the product [21]. The pultrusion process involves filling the die with the material. To ensure the impregnation of the reinforcement fibres, a filling ratio exceeding 100 % is required. The die filling ratio is calculated as the ratio between the cross-sectional area of the input material and the exit area of the die [22,23]. While input material yarns enter the heated dies, the excess melted polymer creates a backflow, which contributes to the impregnation pressure [24]. From that point on, the material is referred to as a pultrudate. It should be noted that the polymer backflow buildup can block the flow path for subsequent material, potentially leading to fibre damage and resulting in an interruption of the process. To avoid such situation, a series of short dies has been found to mitigate the adverse effects of the back flow [18]. Subsequently, the pultrudate enters a cooling die. The cooling die maintains pressure while the composite temperature cools down. Its purpose includes preventing deconsolidation and facilitating shrinkage for releasing the pultrudate from the die surface [22]. In recent publications, a sequence of heated dies arranged with a decreasing final cross-section was employed to enhance impregnation in thermoplastic composites [18,19,22,25–27]. This multi-die pultrusion system was used to produce Flax/PLA [19], Flax/PP [28], C/PEI [22,23] and C/PEEK [18,22] rods with low void volume content. These studies have demonstrated the efficacy of the multi-die pultrusion system in enhancing impregnation.

Surface imperfections manifested as rough fibre finish on the composite surface are caused by a phenomenon known as sloughing in pultrusion terminology [24]. Sloughing is common to thermoset and thermoplastic pultrusion and is attributed to polymer adhesion to the metallic die surface. During pultrusion, as the composite is getting pulled through the cooling die, if polymer-metal adhesive forces are higher than the composite strength, fragments of the pultrudate can tear

off [22]. Carlsson and Astrom [24] compared the imperfections caused by sloughing with different cooling die temperatures and pulling speeds. Alsinani et al. [22] proposed to minimize the apparent sloughing critical distance which was considered to be the distance where the composite temperature is between the processing temperature and the glass transition temperature (T_g). In order to mitigate the sloughing phenomenon, composite shrinkage must be exploited. Where in the case of semi-crystalline polymers, shrinkage occurs during crystallization, which happen at temperature higher than T_g [22]. For both mentioned studies, surface finish was characterized using the roughness parameter. It is suspected that increasing composite strength would reduce the probability of sloughing [29] and that polymer-rich surface could lead to excess sloughing [30]. These propositions lead to the potential for a correlation between yarn tension and sloughing. Seeing that yarn tension induces yarn diameter compaction, which reduces transverse permeability of the fibres [11] and leads to polymer-rich areas around the compacted fibres.

The quality of a composite is typically assessed through reinforcement fibre tow impregnation, as it directly influences mechanical properties. Low fibre tow impregnation decreases the mechanical performance [31]. The fibre tow impregnation is most frequently analysed by measuring the void content [32]. Another route to characterize impregnation quality is by measuring the shear strength of the composite. Shear strength is affected by the composite constituents' individual properties, fibre-matrix interfacial strength, and void content [33]. For a given composite material, different manufacturing conditions has a greater influence on the latter than the first two. Studies have shown a decrease of more than 50 % in in-plane shear strength when the void content increased from 1 % to 4 % [18,34]. This suggests that conducting in-plane shear testing offers a reliable method for assessing composite quality.

Statistics reveal that approximately 80 % of consumed plastics are thermoplastics, with half of them utilized in single-use applications [35]. Among these plastics, polyethylene terephthalate (PET) stands out as the most manufactured polyester globally, extensively employed in beverage bottles, packaging, clothing, and carpeting [36]. Despite the annual collection of significant amounts of recyclable thermoplastics such as PET, finding viable markets for these materials remains a major obstacle [37]. Notably, pultruded thermoplastics possess the potential to be repurposed by chopping them into chips for use as short fibre-reinforced thermoplastics. These can be used in moulding automotive body panels, doors, and fenders, or for panels and housings in the appliance industry [37]. Alsinani et al. [38] used pultruded thermoplastic composites as feedstock for injection moulding. Krastova et al. [39] demonstrated the feasibility of recycling thermoplastic pultruded composites through compression moulding under specific reforming and heating conditions to produce unidirectional plates. A comprehensive study has evaluated various recyclable thermoplastics for their suitability in the pultrusion market [37]. Their findings indicate that PET emerges as the first choice based on its mechanical and thermal properties, cost-effectiveness, and recyclability. Few publications were found using PET as the polymeric matrix. Asensio et al. [17] used recycled PET as matrix and E-glass fibres as reinforcements. Three types of recycled PET matrix were used in their study, one recycled from bottle waste, the second was the same recycled PET for bottle waste though it was modified to lower its viscosity and the third one was a multi-layered and coloured recycled PET. All three materials were ground into powders and transformed into towpregs before pultrusion with 45 % matrix weight content. The pultruded profile was a 20×2 mm² bar. The pultrusion process speed was at 200 mm/min, processing temperature was set at 280 °C and cooling die temperature at 25 °C. The pultruded profiles had an average of 64 % fibre volume content and an average tensile modulus of 47 GPa. There were no quantitative measures for void content. The pultruded plate containing the modified PET with lower viscosity indicated the highest tensile modulus and lowest void content. The study did not analyse yarn tension or surface finish. This

experimental study confirmed the feasibility of recycled PET pultrusion. Volk et al. [40] recently published a study on thermoplastic pultrusion using PET as their polymer matrix. A commingled yarn material containing PET and E-glass with a fibre volume content of 55 % was used during this study. The pultrusion subsystem consisted of a batch pultrusion approach, which allowed the manufacturing of a pultruded rod with limited length of 1500 mm. The batch pultrusion consisted of pulling a loop of input materials by the means of a steel wire. This approach was not continuous and did not necessitate a creel. This indicated that there was no tension applied on the yarn at the beginning of the pultrusion. Throughout their experiments, processing and cooling temperatures remained at 260 °C and 30 °C respectively. Multiple speeds and preheating temperature were tested for different rod diameters. The study indicated that for speeds below 100 mm/min and for different rod diameters, the void content was below 2 %. Micrographs showed an inhomogeneous fibre distribution over the cross-section, suggesting that the fibre arrangement within the yarns and prior to pultrusion, significantly affects the consolidation quality of the pultrudate. Assisted by the transparent die developed in their study, it was observed that the yarn bundles increased in diameter upon entering the die's tapered section and their configuration appeared somewhat entangled. Through the straight section of the die, the bundle of yarns appeared as if they were straightening. A crucial point to consider would be the absence of yarn tension and guidance in this study. No characterization was conducted on the effect of the entanglement or waviness of the commingled yarns on the pultruded rods. Evidently, an investigation into the effect of the absence of tension on the quality of the pultrudate is necessary.

The absence of yarn tension during composite manufacturing may induce fibre waviness. The reason behind this is attributed to the response of thermoplastic fibres to heating. The thermoplastic fibres included in the input materials are produced through a melt spinning process, which results in thermoplastic fibres with low crystallinity and high residual stresses [41]. During heating, these residual stresses are released, resulting in the shrinkage of the thermoplastic fibres [18]. In the input materials, such as commingled or CW yarns, thermoplastic fibres are in close contact with the reinforcement fibres. Due to that contact, when the input materials are heated, the shrinkage of the thermoplastic fibres could induce entanglement or waviness in the reinforcing fibres. Several studies on non-pultruded composites have found that fibre waviness and misalignment contribute to the reduction of the mechanical performance of the composites. Yokozeki et al. [42] presented a numerical model and experimentally validated a reduction of 40–50 % in flexural strength due to fibre waviness. Bogetti et al. [43] showcased a simulation revealing a 40 % decrease in unit cell strength with increasing waviness of [90/0/90] composite laminate under uniaxial compression. In Karami et al. [44] micromechanics model, the results predicted that the Young's modulus in the fibre direction would decrease rapidly with the increase of fibre waviness. Chun et al. [45] included a simulation and an experimental validation demonstrating that the strength of the composite material decreases while the ultimate strain increases with the increase of fibre waviness. Additionally, Potter et al. [46] demonstrated that aside from directly affecting composite properties, fibre waviness influenced the variability in fibre or polymer content of composites. For pultruded thermoplastic composites, Lapointe et al. [18] identified that 3 N tension prevented yarn damage during thermoplastic pultrusion of C/PEEK rods of commingled yarns. By comparing experiments having 0 N tension and 3 N tension, fibre damage was apparent during their 0 N tension experiment and resulted in an interruption of the pultrusion. The yarn damage was attributed to the misalignment of the carbon fibres in the commingled yarns, with the author suspecting that this misalignment was induced by thermoplastic fibre shrinkage. Further investigation is required to explore the effect of thermoplastic fibre shrinkage on fibre waviness formation during thermoplastic pultrusion.

The objective of this study is to demonstrate an effective pultrusion

of DREF yarns at different tension levels and highlight the effect of shrinkage of continuous polymer fibres on composite properties and pultrusion outcome. Glass/polyethylene terephthalate (G/PET) hybrid yarns were used as input materials. First, a comparative discussion on the input materials' CW and DREF structure and their reaction to heating was conducted. Pultrusion experiments were conducted to produce cylindrical profiles, employing the CW and DREF yarns as input materials with in-creel tension levels of 0 N and 3 N. The impact of tension on void content, sloughing, mechanical properties and fibre waviness was analysed for both CW and DREF yarn rods.

2. Experimental

2.1. Materials

The pultrudates were made from glass fibres (GF) as the reinforcement and Polyethylene terephthalate (PET) thermoplastic polymer matrix. Two types of input material were used. The first type was a CW yarn (Concordia Fibers LLC). The second type was a friction spun yarn, a.k.a DREF (Filspec Inc). The PET polymer properties for DREF and CW yarns are shown in Table 1. The melting point (T_m), glass transition (T_g) and degradation temperatures were obtained by DSC (MDSC 2000, TA instruments). Solid density was measured by Pycnometer (Accupyc 1340, Micrometrics). PET's solid density of 1.43 g/cm³ in DREF yarns, was higher than the PET's 1.38 g/cm³ density in CW yarns. This is attributed to the additives added to the DREF's PET to modify its colour to black. The melt density was measured by PVT (pvT 100, ThermoHaake).

The lower left side of Fig. 1 shows a magnified image of the longitudinal and cross-sectional illustration of both CW and DREF tows. PET fibres and GF were represented in black and white respectively. The CW tow sketch is an assembly of one PET tow and one GF tow. The CW illustration reveals the parallel placement of the GF and PET fibres, as well as the continuous nature of the PET fibres. The DREF tow sketch shows GF enclosed by the spun PET discontinuous fibres. The CW yarns were composed of PET fibres (Laser + HS Ti818) and E-GF (ECDE75, AGY). One CW yarn is an assembly of seven PET tows of 100 tex each and 20 E-GF tows of 66 tex each. E-GF density was of 2.54 g/cm³. The total linear density of one CW yarn was 2020 tex. It included 700 tex of PET and 1320 tex of E-GF. DREF yarns were composed of PET fibres (staple fibre, Huvis Corporation) and S2-GF (SCG75, AGY). A DREF tow was comprised of discontinuous PET fibres, amounting to 38 tex, friction spun around one S-GF tow of 66 tex. S-GF density was of 2.46 g/cm³. Eight tows were assembled without a twist, to shape one DREF yarn. The total linear density of one DREF yarn consisted of 832 tex, with 304 tex of PET fibres and 528 tex of S-GF.

2.2. Pultrusion apparatus

Fig. 1 illustrates the schematic of the pultrusion system used for this study. The apparatus consisted of a creel, a guiding plate, a preheater, three heating dies, one cooling die, cooling fans, a load-cell, an encoder and a pulling system. At the initial stage of the pultrusion system was a creel housing bobbins of yarns. The creel allowed holding up to 50 bobbins and applies tension by modulating the friction on the bobbins to restrain their rotation. The tension of each yarn from the bobbins was

Table 1
PET polymer properties in CW and DREF yarns.

	CW yarn's PET	DREF yarn's PET
Melting point (°C)	254	257
Glass transition (°C)	80	80
Degradation temperature (°C)	295	295
Solid density (g/cm ³)	1.38	1.43
Melt density (g/cm ³)	1.06	1.06

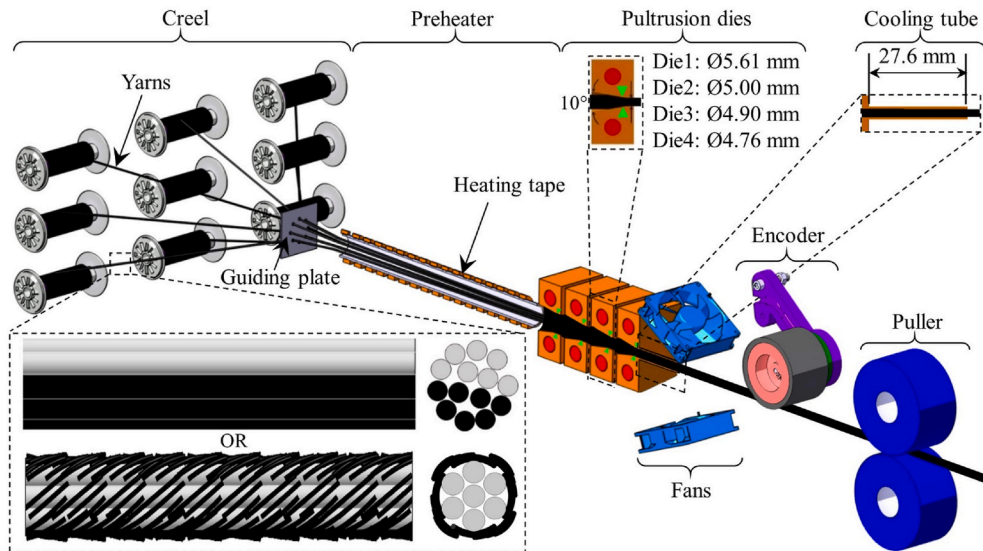


Fig. 1. Schematic view of the thermoplastic pultrusion system used showing a transverse cross-section of the preheater and the pultrusion dies. Each component of the pultrusion system is labelled and identified accordingly. Red circles represent the heat cartridge location, and the green triangles represent the control thermocouple locations. On the lower left side is an illustration of the longitudinal and cross-section view of a both CW and DREF tows where PET and GF are represented in black and white respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

calibrated using a digital fish scale. The guiding plate was used to position the yarns for entry into the preheater and obtain a controlled arrangement. The preheater featured a metallic tube measuring 300 mm in length and 16.2 mm in diameter. A heating tape was wrapped around the metallic tube to provide heat. Heating of the pultrusion dies was carried out using heating cartridges represented by the red circles. The temperature was monitored by type J thermocouples, visually indicated by the green triangles in Fig. 1. The pultrusion dies serve the purpose of shaping the composite structure by combining and impregnating the reinforcement fibres with the polymer matrix. All four dies had a 10° tapered cavity with a length of 31.75 mm followed by a cylindrical cavity with a length of 6.67 mm. The dies' cylindrical cavities had exit

diameters of 5.61, 5.00, 4.90 and 4.76 mm respectively. The dies were separated by a 5 mm gap. This multi-die configuration was similar to previously published study that showcased good pultrudate impregnation quality [22]. The last die had a thin-walled tube with a length of 27.6 mm for cooling purposes, as detailed in Ref. [22]. The tube length was subjected to the airflow generated by the fans. A puller controlled the pultrusion speed with an encoder monitoring the real-time speed. Fig. 2 (a) shows an image of the actual thermoplastic pultrusion system used in the study. The pultrusion direction is presented by a red arrow. The image shows DREF yarns being guided through the guiding plate, they then pass through the preheater, three heating dies, and the composite then exits through the cooling die where cooling fans are located.

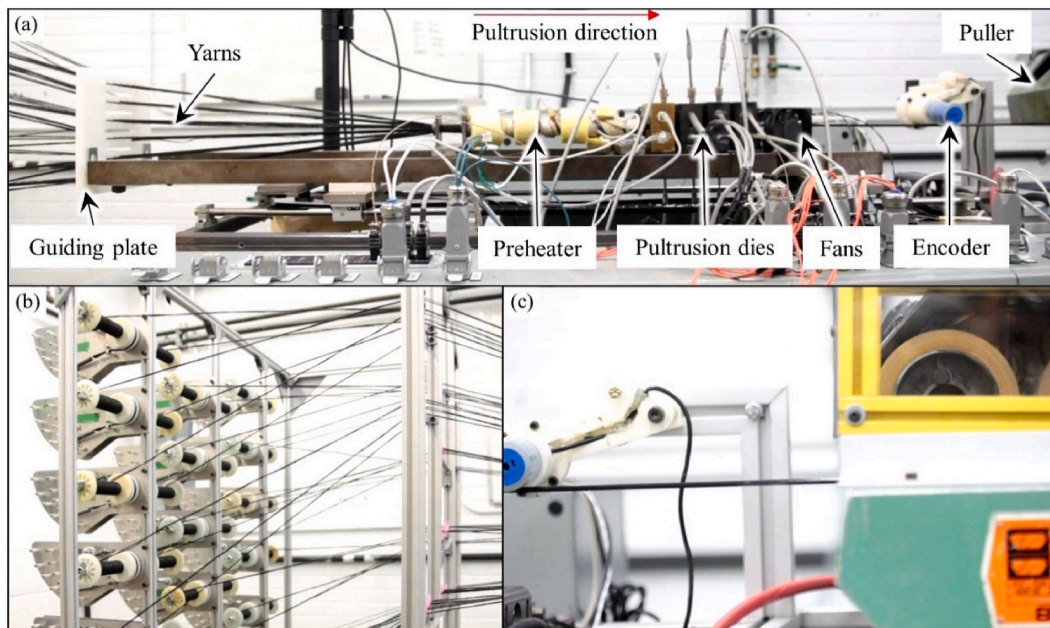


Fig. 2. (a) Image of the actual thermoplastic pultrusion system used. The pultrusion direction is presented by a red arrow. Each component of the pultrusion system is labelled and identified accordingly. (b) Image of the creel filled with bobbins of DREF yarns with tension applied. (c) Close-up image showing the encoder and puller. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

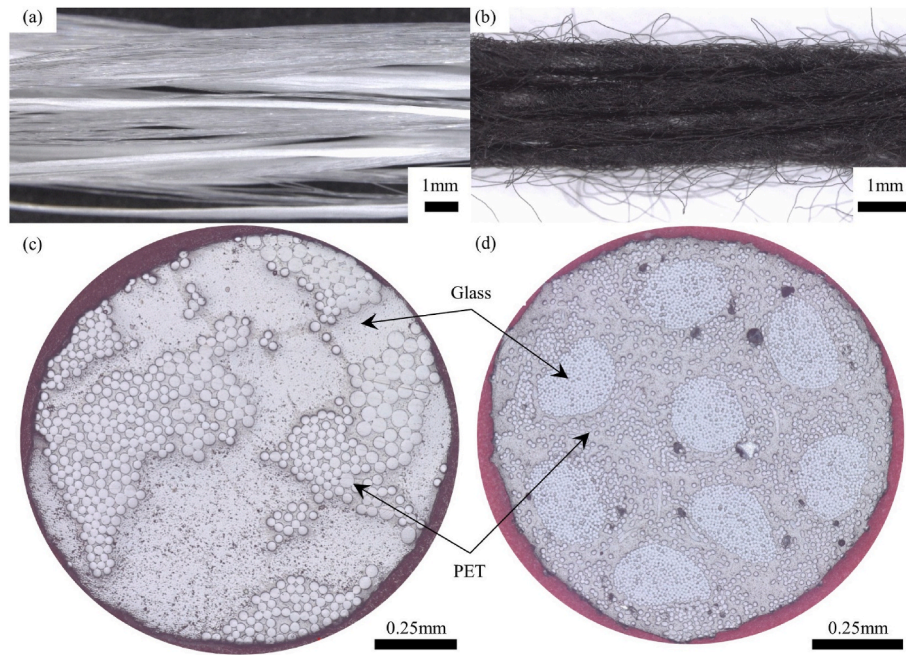


Fig. 3. Input material yarns structures of (a) CW yarns (b) DREF yarns, and cross-sectional micrographs at a 200 magnification of (c) CW yarns (d) DREF yarns.

Fig. 2 (b) shows the creel housing the bobbins of DREF yarn under tension. Fig. 2 (c) shows a close-up view of the encoder and the pulling system used to pull the composite.

2.3. Pultrusion experiment

The pultrusion system shown in Fig. 1 was used to manufacture 5-m-long GF/PET rods. Table 2 displays the sample name, material, tension, standardized tension, number of yarns, filling ratio ($Rf_{die\ i}$) of each die and the theoretical fibre volume content ($v_{f,th}$) for each experiment. The sample name consisted of the input material with the respective tension used. Two different tension adjustments were applied during the experiments. The first condition included the application of three N (3 N) tension to each bobbin, while the second involved no tension (0 N). Considering that the yarns carried by each bobbin did not have the same size (fineness), a standardized force (N/tex) was calculated. The standardized tension in CW yarns was 0.0015 N/tex and 0.0036 N/tex for DREF yarns. The filling ratio was calculated for each pultrusion die and is expressed by the equation,

$$Rf_{die\ i} = (A_f + A_{m,i-1}) / A_{die\ i} \quad i = 1, 2, 3, 4 \quad (1)$$

where A_f is the total GF cross-sectional area and $A_{m,i-1}$ is the PET cross-sectional area located before the i th die. $A_{die\ i}$ is the die's exit area calculated with the exit diameters of each die respectively. A_f was determined by,

$$A_f = \frac{N \times F_f}{1000 \cdot \rho_f} \quad (2)$$

where N is the number of input material yarns used in each pultrusion

experiment. F_f is the linear density of the GF in tex, and ρ_f the solid density of the GF in g/cm³. Note that the cross-sectional area of the GF is constant throughout the pultrusion. The PET cross-sectional area at the first die entrance can be calculated with,

$$A_{m,0} = \frac{N \times F_m}{1000 \cdot \rho_m} \quad (3)$$

where F_m is the linear density of the PET in tex, and ρ_f the melt density of the PET in g/cm³. If the filling ratio $Rf_{die\ i}$ is exceeding 100 % and considering that the GF are impregnated at each die, the PET cross-sectional area entering the die $i+1$ is equal to the PET exiting the i th die. This can be calculated with,

$$A_{m,i} = A_{die\ i} - A_f \quad i = 1, 2, 3, 4 \quad (4)$$

The filling ratio should exceed 100 % to insure consolidation during pultrusion. Table 2 indicates that the first die's filling ratio did not exceed 100 %. Actually, the purpose of the first die was to ensure that all polymer fibres were reaching the processing temperature without significant polymer flow. To achieve comparable consolidation in all experiments, the number of yarns (N) was adjusted to get similar filling ratios between CW and DREF experiments. The theoretical fibre volume content for the pultruded rod is calculated according to,

$$v_{f,th} = A_f / (A_f + A_{m,4\ solid}) \quad (5)$$

where $A_{m,4\ solid}$ is the PET's solid cross-sectional area in the die 4 as it accounts for the shrinkage that occurs upon cooling, and can be calculated with,

$$A_{m,4\ solid} = A_{m,4} \times 0.8 \quad (6)$$

Table 2

Variable pultrusion parameters used for each experiment.

Sample name	Material	Tension	Standardized Tension	N	$Rf_{die\ 1}$	$Rf_{die\ 2}$	$Rf_{die\ 3}$	$Rf_{die\ 4}$	$v_{f,th}$
CW-3N	CW	3 N	0.0015 N/tex	18	84 %	106 %	104 %	106 %	58 %
DREF-3N	DREF	3 N	0.0036 N/tex	42	81 %	103 %	104 %	106 %	56 %
CW-0N	CW	0 N	0 N/tex	18	84 %	106 %	104 %	106 %	58 %
DREF-0N	DREF	0 N	0 N/tex	42	81 %	103 %	104 %	106 %	56 %

A shrinkage ratio of 0.8 was applied to both polymers since it can be assumed that the melt density of semi-crystalline polymers, like PET, are 0.8 of their solid density [47].

For all pultrusion experiments, the speed was set at 35 mm/min. This pultrusion speed was chosen arbitrarily to compare the impregnation quality between the two different input materials. The preheater temperature was set to 240 °C in order to bring the material closer to its processing temperature. The heating dies were set at 280 °C. PET like other semi-crystalline polymer, crystallizes at temperature between T_g and T_m [48]. The cooling temperature was set between T_g and T_m at around 168 °C to enhance the crystallization. It was observed in Alsani et al. [22] that this temperature resulted in improved dimensional stability and surface finish for a semi-crystalline polymer. Given that the composite is constrained by the die walls the composite rod nominal diameter was considered equal to the diameter of Die 4. Throughout the experiments, a data acquisition system (Labview) recorded the pultrusion parameters.

2.4. Characterisation

Microscopic images of the input materials cross-section were taken to reveal their structures. Input material yarns were enclosed in a shrink tube (Polyolefin Plastic). The shrink tube was uniformly heated to induce tube shrinkage without PET polymer melting. The shrink tape covered yarn were embedded in epoxy resin (Epofix, Struers). Once the epoxy was cured, samples' cross-section was polished and analysed under a microscope (VHX 7000, Keyence). Input materials behaviour under heating was characterized by first securing one end of each yarn with polyimide tape (Kapton® Polyimide Plastic) in a metallic fixture. The yarns were then placed in an oven (F100HP, Pyradia, Brick Oven) at 240 °C for 1 min. A video of the yarns behaviour during heating was acquired.

During each pultrusion experiment, the pultrudate's temperature was acquired with a follow-on 36-gage type J wire thermocouple. The thermocouple was spliced to a yarn in the centre of the pultrudate's cross-section. Pultruded rods were inspected for surface imperfections. Samples were cut for microscopic observations at sloughing defects locations. The rods' diameter was measured using a micrometre (H-2780, Mitutoyo Digital). The defect-free diameter was measured at five locations where the rod appeared fully circular indicating that sloughing did not occur. To assess the sloughing defects, the actual diameter of the pultrudate was measured by performing 60 measurements along a 1-m length of the pultruded rod. Twenty diameter measurements were acquired with 50 mm intervals. This measurement process was repeated three times, with each iteration involving a 45° rotation of the rod. These 60 measurements were acquired without paying attention to the surface finish, roundness, or presence of sloughing defects on the pultruded rods.

Impregnation was characterised by void content analysis and optical microscopy. Constituent content was measured per ASTM D3171-22 procedure G. The void content was calculated in accordance with the same standard where density measurements of samples were carried out following the ASTM D792. For microscopic observation, three samples of 30 mm were cut from each experiment. The cylindrical samples were prepared according to the same procedure than the unconsolidated yarns, described above.

From each pultruded rod, a 50 mm sample was cut and scanned using an X-ray CT system (Zeiss, Xradia-520 versa). These samples were scanned and stitched at two positions overlapping each other, to create a 3D image of a composite rod measuring 10 mm in length. The CT scans were conducted with a voxel size of 6.5 µm using a beam energy of 60 kV and 50 W in power. Subsequently, two sets of 1601 projections were obtained then stitched automatically with Scout-and-Scan Control System (Zeiss, v14.0), for the image reconstruction. The resulting stitched 3D image was comprised of 1850 slices perpendicular to the rod axis. Finally, for segmentation, 3D visualization, and quantitative analysis,

reconstructed images were imported into an image processing software (Object Research Systems Inc. (ORS), Dragonfly software (version 2020.1). For manual segmentation of a specific yarn, 15 slices were chosen at an interval of 100 slices. Then using an interpolation operation tool within the software, the slices between the 15 selected ones were automatically filled to highlight the chosen yarn.

Two mechanical tests were conducted on the composite rods. To assess the elastic modulus of the composite manufactured by each experiment, three rods, each with a length of 150 mm, underwent tensile testing using grooved grips to prevent slipping. The composite rod was securely clamped within 20 mm of the grips from both ends. Elongation was acquired using an extensometer (634.25F-25, MTS) with a gage length of 50 mm. The tensile chord modulus of elasticity was determined by following the ASTM D3039. The strain range was measured at two points, one at 25 % and another at 50 % of the maximum strain. Shear strength was characterized following an adaptation of the ASTM D3914 [19]. Three coupons were tested per experimental conditions. Coupons had a length of 19 mm. Two grooves were cut on each side of the rod using a precision saw (Secotom-20, Struers). The distance between the grooves was 5 mm. The coupons were loaded under compression (Insight, MTS). The maximum compression load was recorded and divided by the rod's longitudinal area between the grooves to obtain the in-plane shear strength.

3. Results and discussions

3.1. Input materials' structure

Fig. 2 (a) shows the microscopic image at 30-x magnification of a CW yarn with a black background. The image shows that the yarn had a flat structure with both GF and PET fibres being white. The CW input material was lacking consistent shape retention and tended to be deformed when touched. Fig. 2 (b) shows the microscopic image at 30-x magnification of a DREF yarn. The image shows an assembly of DREF tows with the GF in white and PET fibres in black. This input material was comprised of short PET fibres that had a soft texture. In some cases where friction levels were elevated during winding, the short fibres tended to be dislodged. However, the yarn maintained a consistent overall shape and exhibited resilience against deformation.

Fig. 3 (c) shows the microscopic image at 200-x magnification of a CW yarns cross-section contained in a shrink tube. The smaller circles represented the GF. The GF are of smaller size compared to those of PET fibres. It was observed that the PET fibres exhibited variations in size. The CW cross section showed unevenly blended bundles of PET fibres and agglomerations of GF. Fig. 3 (d) shows the microscopic image at 200-x magnification of a DREF yarns cross-section, also contained in a shrink tube. The GF are the densely packed particles forming eight agglomerations, while the PET fibres are dispersed around them. The DREF cross section exhibited uniform PET fibres distribution around the GF. The cross section of the CW represented 2020 tex of material, whereas the DREF represented 832 tex of material. However, Fig. 3 (c) and (d) show a yarn diameter of 1.30 mm and 1.15 mm for CW and DREF respectively, this suggested that DREF had a higher bulk factor than CW yarns. The bulk factor refers to the ratio of the volume occupied by the yarn in its uncompressed state to the volume it occupies when fully compacted. A high bulk factor in the yarns may pose challenges during the compression moulding of complexes structures with small corner radii [49]. However, during a linear process such as pultrusion, there is a limited impact of the high bulk ratio of the input material.

Fig. 4 presents both input material yarns behaviour under heat and without tension. Fig. 4 (a) presents CW and DREF yarns placed side by side on a metallic fixture at room temperature. Fig. 4 (b) presents CW and DREF yarns placed side by side on a metallic fixture after being placed in an oven at 240 °C for 1 min. The temperature was set at 240 °C to replicate the response of the yarns as they passed through the pre-heater without tension. A video of the yarns' behaviour under heat is

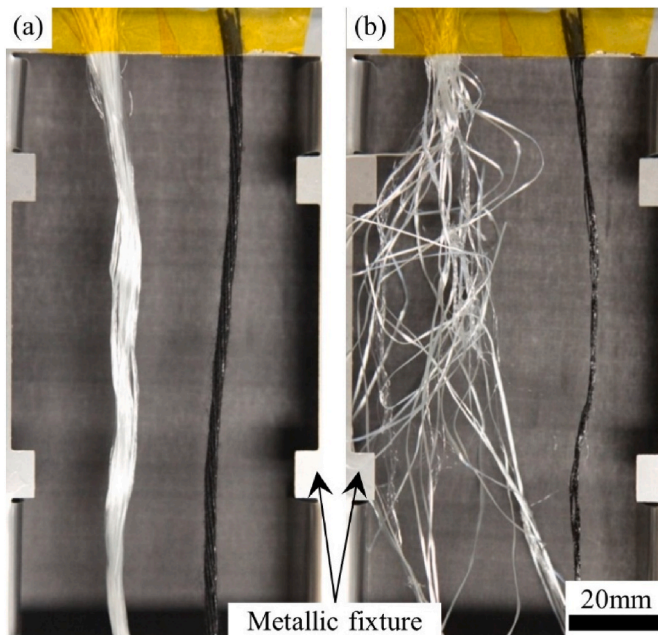


Fig. 4. Un-tensioned CW and DREF yarns shape: (a) before heating, (b) after heating at 240 °C for 1 min.

available at <https://youtu.be/3UNLEjfZRUU>. As demonstrated in Fig. 4 (b), the heating of the CW yarn resulted in an entanglement of the yarn structure. The long PET fibres shrunk before melting which resulted in dragging the reinforcement fibres and caused the waviness of the GF. On the other side, Fig. 4 (b) demonstrated that the DREF yarn kept its structure with GF staying straight after heating. This observation was also apparent during the experiments. In the preheater, when tension was not applied, CW yarns were entangled and entered the dies all scattered. However, the DREF yarns retained their shape and behaved comparably in both experiments, with and without tension. Images of the CW and DREF yarn extracted from the preheater, illustrating the explanation above, are available in the supplementary section S1.

3.2. Pultrusion experiment

Fig. 5 displays a schematic of the transverse cross-section of the preheater and the pultrusion dies with the temperature profile recorded throughout the DREF-ON pultrusion experiment. This temperature profile was similar throughout all the pultrusion experiments. The green triangles represent the fixed thermocouples within the dies and on the cooling tube. The solid line represents the actual temperature measured. The dashed line corresponds to the set points of the preheater and dies

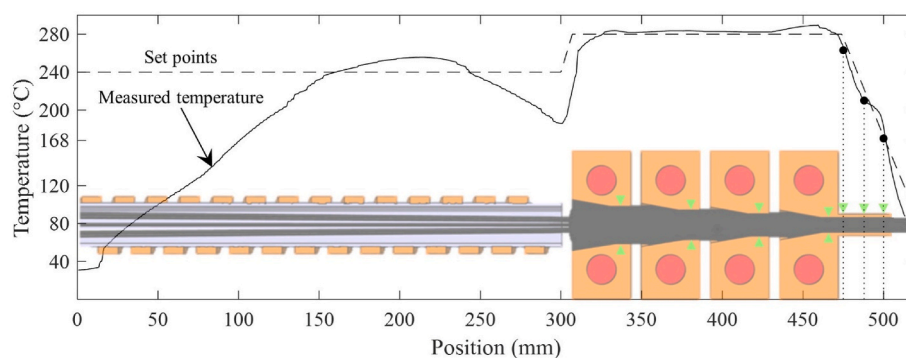


Fig. 5. Temperature measurement and set points during DREF-ON pultrusion experiment. The solid line corresponds the actual reading temperature, while the dashed line corresponds to the set points.

and the desired cooling temperature of the cooling tube. The three black points on the graph represent the measured temperatures of the outside of the tube using glued-on thermocouples. The preheater was set to 240 °C and the dies were set to 280 °C. The cooling temperature at the exit of the thin-walled tube was 168 °C. When entering the preheater, the recorded temperature gradually increased to reach the set point temperature. The temperature reached 240 °C at the second half of the preheater. At the end of the preheater, the temperature lowers due to the small gap between the dies and the preheater. When entering the first die, the temperature rises again. It reached the set point of 280 °C at the middle of the first die. The temperature remained steady at 280 °C in the first three dies. The small gaps did not affect the material temperature. At the middle of the last die the temperature increased to 290 °C, then started dropping before reaching the start of the thin-walled tube. The fans directing airflow onto the die's surface could indirectly cause the temperature raise. This heat extraction by the airflow caused the heating cartridges to overheat the pultrudate at the Die 4 entrance. Then, due to the same airflow heat extraction, the pultrudate started to cool down before reaching the dies exit. The thermocouple placed on the surface of the thin-walled tube indicated temperatures comparable to those measured inside of the composite. The temperature decreased at the beginning of the tube from 234 °C to the middle at 205 °C and reached 168 °C at the tubes exit. The measured temperature along the pultrusion experiments aligns with temperature expectations values.

3.3. Sloughing defects assessment

Fig. 6 show photographs and cross-section microscopies of pultrudates where sloughing defects were apparent. Fig. 6 (a) and (b) displays the microscopic image at 20-x magnification of the CW-3N and DREF-3N rods. The pultrusion direction was displayed on the images. Both images showed an aggregate of polymer-rich surface that was ruptured during the pultrusion with a diameter of 4.69 mm for the CW-3N rod and 4.57 mm for the DREF-3N rod. The aggregates had adhered to the cooling tube wall and subsequently de-bonded under the pressure from the incoming pultrudate. Before debonding, the aggregate ploughed into the pultrudate surface and caused a reduction in the pultrudate diameter and rough surface finish. The rough surface had visible GF with a smaller diameter of 4.18 mm for the CW-3N rod and 4.49 mm for the DREF-3N rod. Fig. 6 (c) and (d) presents the microscopic image of the cross-section of a CW-3N and DREF-3N sample that included a sloughing defect. The upper sections of the images in Fig. 6 (c) and (d) show the sloughing defect as a marginally detached fragment of the pultrudate. The sloughing defects reveal minimal GF presence as depicted in the enlarged view. Sloughing defects were observed in all experiments, but the exact extent or frequency of these events cannot be determined through this local observation alone. A diameter measurement distribution is provided below to quantify the intensity of the sloughing defects. In the literature, surface finish was characterized

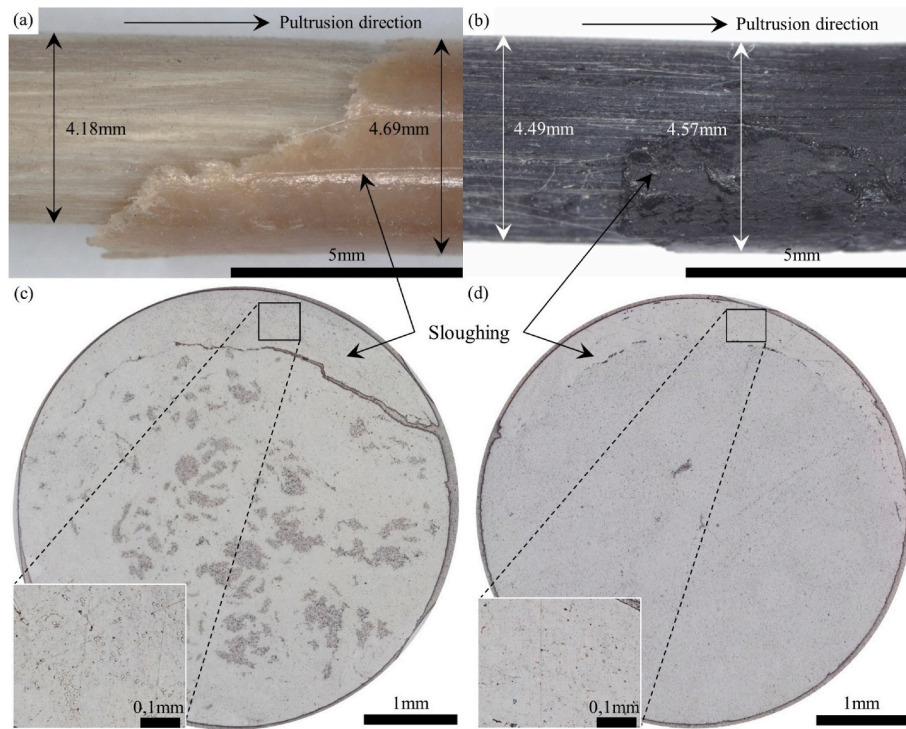


Fig. 6. Top: Photographs at 20-x magnification of GF/PET rods at a section showing sloughing defects on the CW-3N (a) and DREF-3N (b) rods. Bottom: Cross-section image of the GF/PET rods at a section showing sloughing defects of CW-3N (c) of DREF-3N (d).

using the roughness parameter [22,24]. However, in the current study, distributed diameter measurements were deemed to be more accurate for characterizing sloughing defects intensity.

Fig. 7 presents the corresponding diameter measurements for the CW-3N, DREF-3N, CW-0N and DREF-0N. Displayed error bars for each experiment are the standard deviations on each measurement. The

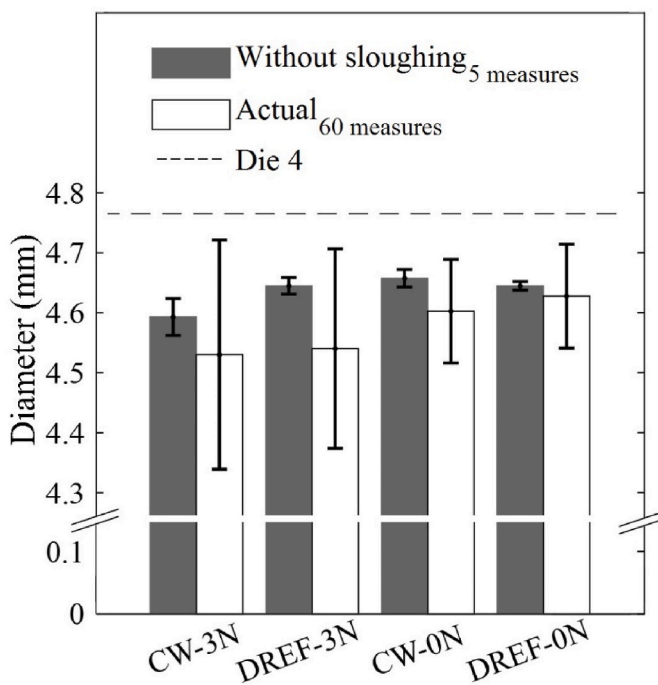


Fig. 7. Average of the five diameter measurements on selected locations without sloughing and average of the 60 diameter measurements for CW-3N, DREF-3N, CW-0N and DREF-0N.

dashed line shown in the bar graph represented the 4.76 mm exit diameter of the Die 4. The average of the five diameter measures where sloughing defects did not occur (i.e. 'Without Sloughing') are presented in grey. CW-3N and DREF-3N diameters without sloughing defects were 4.59 ± 0.03 mm and 4.64 ± 0.01 mm respectively. CW-0N and DREF-0N diameter without sloughing defects was 4.66 ± 0.02 mm and 4.64 ± 0.01 mm. These diameter measurements are relatively close to each other. The variation observed between the diameter without sloughing defects and the exit diameter of the Die 4 was caused by the pultrudate's shrinkage. The average of 60 equidistant diameter measures along the 1-m-long rod representing the 'Actual' diameter are presented in white. The rods made using yarn tension of 3 N had the lowest actual average diameters with the largest standard deviation on the 60 equidistant measurements. CW-3N and DREF-3N actual diameters were 4.53 ± 0.19 mm and 4.54 ± 0.17 mm, respectively. The rods made using no yarn tension had an actual average diameter closer to the 'Without Sloughing' diameters and with standard deviations almost half of the 3 N tension experiments. CW-0N and DREF-0N actual diameters were 4.60 ± 0.09 mm and 4.63 ± 0.09 mm. The smaller standard deviations for CW-0N and DREF-0N indicates that when tension was not applied (0 N), the diameter was more consistent and exhibited less variation. Remarkably, for the DREF-0N, the actual diameter was the closest to its diameter without sloughing (with 0.02 mm difference). Indicating that DREF-0N had the least number of sloughing defects. This confirms visual observations during the experiment.

These observations revealed that tension influenced the diameter variation of the rods. Yarn tension induces yarn diameter compaction [18], thereby resulting in lowering transverse permeability of the fibres [11]. As a result, the polymer formed a layer around the bundle of the compacted fibres. Since a limited number of fibres are present in the polymer-rich layer, the adhesion force exceeded the strength of the composite, resulting in the detachment of the polymer-rich layer and the creation of sloughing defects. Additionally, the sloughing defects observed suggested that the cooling process might have been inadequate. While the focus of this study did not revolve around the pultrusion cooling process, improvement of the cooling should be

investigated in future studies.

3.4. Impregnation assessment

Fig. 8 (a) shows the fibre volume fraction of CW-3N, DREF-3N, CW-0N and DREF-0N. The theoretical fibre volume fraction $v_{f,th}$ of 58 % for CW-3N and CW-0N is shown with a dashed line. Whereas the theoretical fibre volume fraction $v_{f,th}$ of 56 % for DREF-3N and DREF-0N is shown with a dotted line. Displayed error bars for each experiment are the standard deviations on three measurements. Fibre volume fraction was measured at 62.0 ± 0.3 %, 59.4 ± 0.5 %, 59.9 ± 1.1 % and 56.0 ± 0.7 % for CW-3N, DREF-3N, CW-0N and DREF-0N respectively. For CW-3N and DREF-3N, the average measured v_f values were noticeably higher than the $v_{f,th}$ with a 4.0 % and 3.4 % discrepancy respectively. The effect of sloughing is likely to have been the cause for this high discrepancy. For CW-0N and DREF-0N, the average measured v_f values exhibited a 1.9 % and 0.0 % discrepancy on the $v_{f,th}$ respectively. In the previous section, CW-3N and DREF-3N demonstrated to have more sloughing defects than CW-0N and DREF-0N. It was explained that yarn tension induced fibre tow compaction, which lead to the presence of a polymer-rich area around the bundle of the compacted fibres and thereby resulted in polymer adhesion. The adhered polymer's ploughing reduces the effective diameter of the Die 4. Consequently, for the same amount of fibres, less polymer was able to exit the Die 4. This resulted in a higher v_f for CW-3N and DREF-3N. It is important to note that the v_f was measured by pyrolysis and calculated using the actual density of the pultrudate. The actual density was measured through liquid immersion. For CW-0N, the standard deviation on the average measured v_f was the highest (1.1 %). Indicating that on samples that were characterized, there was a significant variation in the GF volume content. Fibre waviness may have contributed to the variation in the GF volume content of CW-0N. The evaluation of waviness is detailed in Section 3.5. For DREF-0N, average measured v_f showed low standard deviation and an insignificant discrepancy on the $v_{f,th}$. Demonstrating that for DREF-0N the average measured v_f was consistent with the theoretical predictions. This correlates with the previous section that indicated negligible number of sloughing defects. From the results above, it is likely that higher v_f is caused by yarn tension that increased the sloughing defects occurrence in CW-3N and DREF-3N. In the case of CW-0N, the higher v_f was attributed to fibre waviness.

Fig. 8 (b) shows the void content of CW-3N, DREF-3N, CW-0N and DREF-0N. The void content v_v was measured at 4.2 ± 0.4 %, 2.9 ± 1.0 %, 2.2 ± 1.0 % and 1.1 ± 0.1 % for CW-3N, DREF-3N, CW-0N and DREF-0N respectively. These measurements indicated that when 3 N

tension was applied v_v was higher than when no tension was applied (0 N). This observation, also observed by Laponite et al. [18], is explained by the lower permeability of the compacted fibre bundle due to the tension. For the non-tensioned pultrusions, CW-0N v_v average was higher and had a larger standard deviation than DREF-0N. The greater v_v value of the CW-0N was attributed to the structure of the input material by itself. As explained in Section 3.1, CW yarns displayed unevenly blended bundles of PET fibres and greater agglomerations of GF. Large bundles of GF require more time for impregnation. DREF yarns have PET fibres well dispersed around the constant size GF bundles therefore requiring shorter time for impregnation as well as a similar impregnation time between GF bundles. In summary, both larger size of GF agglomerations in hybrid yarns, as well as higher yarn tension, increased the void content of the pultrudates.

Fig. 9 (a) and (b) presents microscopic images of the cross-section of samples from CW-3N and DREF-3N. All black areas with different dark tonalities represent voids. The enlarged views show a bundle of un-impregnated fibres. Through the comparison Fig. 9 (a) and (b), it was clear that the agglomerations of un-impregnated fibres were noticeably larger in CW-3N than of DREF-3N. This was directly linked to the better distribution of GF in the DREF yarns as shown in Fig. 3. Fig. 9 (c) presents the microscopic image of the cross-section of a sample from CW-0N. This cross-section still presented black areas scattered around the image. Fig. 9 (d) presents the microscopic image of the cross-section of a sample from DREF-0N. This image shows an insignificant number of black areas. The cross-section appears to be very well impregnated. Indicating that DREF yarns showed notable improvement in impregnation without tension. These images directly align with the v_v measurement shown in Fig. 8. For Fig. 9 (a) and (b), where a 3 N tension was applied for both experiments, the porosity was remarkable. Therefore, once again validating that having extensive tension can lead to the compaction of the fibre bundles and reduces permeability and thus limits impregnation. However, in the case of the CW yarns, tension absence did not enhance impregnation. This was due to the CW yarn structure, precisely the size of GF agglomeration. Conversely, the structure of DREF yarns enabled achieving high impregnation without any application of tension during pultrusion.

3.5. Waviness assessment

Fig. 10 presents CT-scan images of 10 mm-long GF/PET pultruded rods with four-coloured glass fibre bundle (blue, purple, yellow and red). Fig. 10 (a) shows a CT scan image of a CW-0N pultrudate showing four wavy GF tows. Fig. 10 (b) shows a CT scan image of a DREF-0N pultrudate showing four straight GF tows. CT scan images clearly

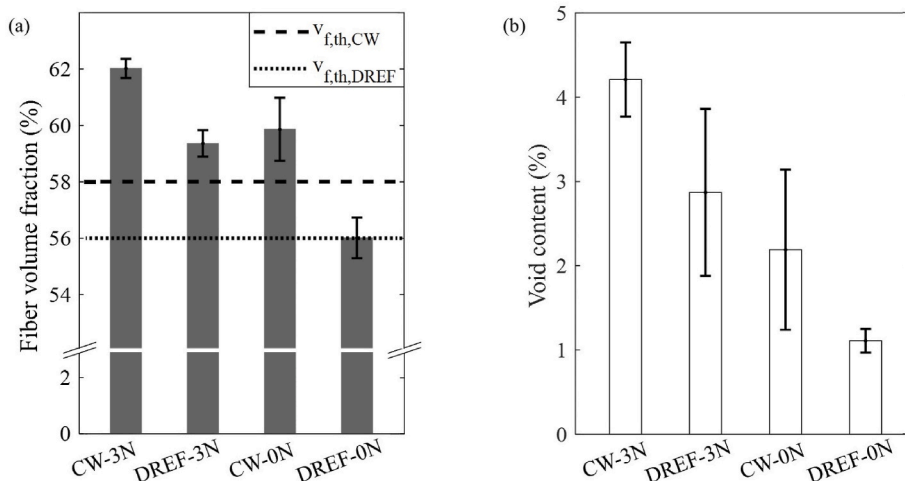


Fig. 8. (a) Fibre volume fraction of CW-3N, DREF-3N, CW-0N and DREF-0N. (b) Void content of CW-3N, DREF-3N, CW-0N and DREF-0N.

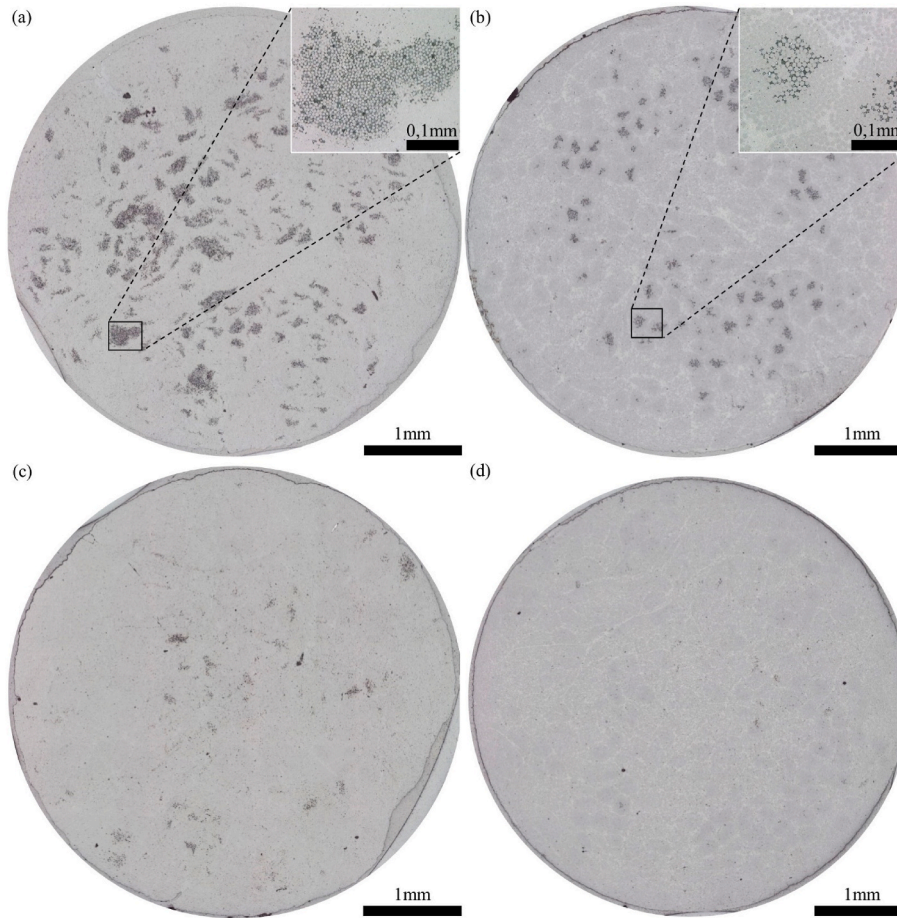


Fig. 9. Cross-sectional images of the pultruded G/PET rods for (a) CW-3N (b) DREF-3N (c) CW-0N, and (d) DREF-0N.

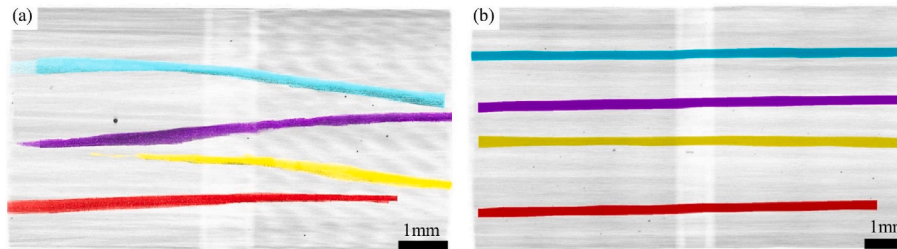


Fig. 10. CT scan images of the pultruded GF/PET rods for (a) CW-0N showing four wavy fibre tows (b) DREF-0N showing four straight fibre tows.

illustrated that when no tension was applied during the pultrusion of CW yarns, fibre waviness occurred. Conversely, when no tension was applied to DREF yarns, fibre tows retained their form and remained straight throughout the pultrusion process. This contradicts the findings of Volk et al. [40], who observed apparent straightening of commingled in the straight section of the die. CT-scan image of CW-3N and DREF-3N pultrudates were not evaluated considering that yarn tension straightened the yarns in both cases. The findings presented here support that the absence of yarn tension during composite manufacturing induces fibre waviness in input materials consisting of continuous thermoplastic fibres, like CW yarns. Whereas, for DREF yarns consisting of discontinuous thermoplastic fibres, fibre waviness remains absent even without the application of tension.

3.6. Composites mechanical properties

Fig. 11 presents the elastic modulus of the GF/PET rods. Theoretical

elastic modulus for CW experiments (E_{CW}) is presented in a dashed line, with a value of 43.27 GPa. Theoretical elastic modulus for DREF experiments (E_{DREF}) is presented in a dotted line, with a value of 51.98 GPa. These theoretical values were calculated using $v_{f,th}$, E-GF (69 GPa) and S-GF (86 GPa) elastic modulus from material's technical datasheets. The elastic modulus of PET was (3.6 GPa) [50]. The bar graph displays the measured elastic modulus (E) in GPa of samples from CW-3N, DREF-3N, CW-0N and DREF-0N experiments. Displayed error bars for each experiment are the standard deviations on three samples and are small compared to the modulus differences between experiments. Comparative analysis between CW and DREF experiments was challenging due to the difference in GF types. It should be noted that the theoretical elastic modulus E_{CW} and E_{DREF} were calculated based on $v_{f,th}$. However, the experimental v_f (Fig. 8 (a)) was higher than the theoretical values. This discrepancy accounts for the observed difference between the theoretical and experimental values of the elastic modulus. CW-3N and CW-0N presented close comparable values of 48.87 ± 0.19 GPa

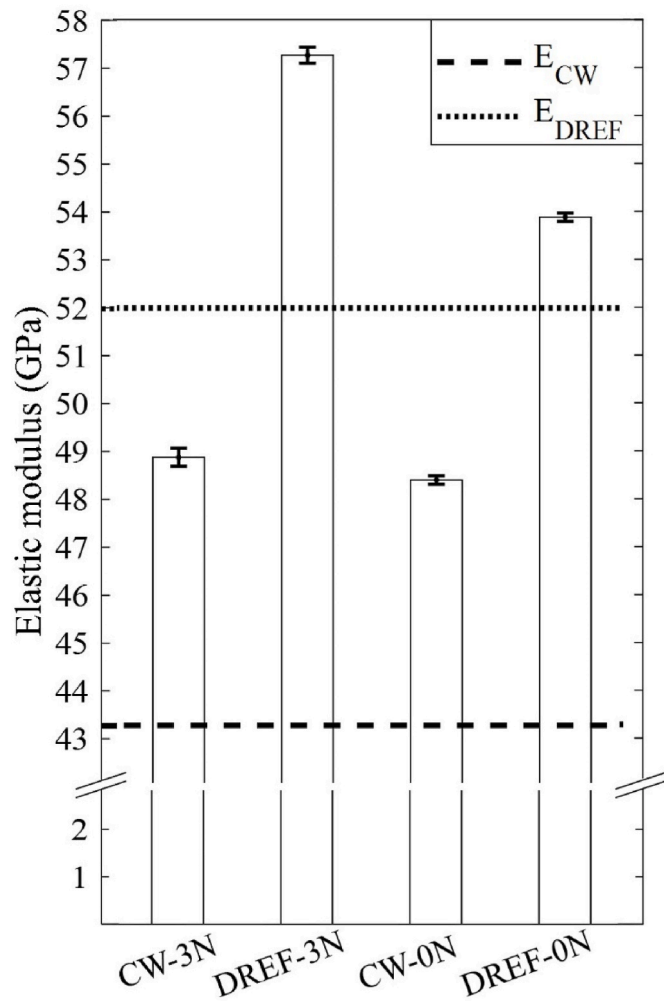


Fig. 11. Elastic modulus of GF/PET rods for CW-3N, DREF-3N, CW-ON and DREF-ON. Dashed and dotted lines show the theoretical elastic modulus.

for CW-3N, and a 48.39 ± 0.09 GPa for CW-ON. It should be noted that CW-3N exhibited higher void content than CW-ON. However, the similar modulus values are explained by the similar volume fraction of the CW pultrudates (see Fig. 8 (b)). DREF-3N elastic modulus was 57.26 ± 0.17 GPa. The DREF-ON modulus was 53.88 ± 0.09 GPa. Although DREF-3N showed higher void content than DREF-ON, the 3.35 GPa lower value for DREF-ON is explained by the significantly lower fibre volume fraction of the DREF-ON pultrudates (see Fig. 8 (a)). This indicated that while void content negatively impacts the mechanical properties of composites, their effect on the elastic modulus was seen to be less pronounced than the effect of v_f .

Although the use of PET in pultrusion is relatively rare, one notable study by Asensio et al. [17] provides relevant data. The comparison indicates a close alignment between the above-mentioned values and those reported by Asensio et al. [17]. For instance, Asensio et al. [17] found a tensile modulus of 47 GPa, with a 64 % fibre volume fraction while the tensile modulus for CW-3N where E-GF were also used with a 62 % fibre volume fraction indicated an average of 49 GPa.

Fig. 12 presents the in-plane shear strength of the GF/PET rods. Displayed error bars for each experiment are the standard deviations on three samples. The in-plane shear strength was 26.93 ± 4.51 MPa, 55.47 ± 2.39 MPa, 55.17 ± 15.17 MPa and 119.35 ± 16.89 MPa for CW-3N, DREF-3N, CW-ON and DREF-ON. The bar graph demonstrates a noticeable increase in the in-plane shear strength across the four experiments, progressing from CW-3N to DREF-ON. This was consistent with the decrease in void volume fraction shown in Fig. 8 (b). Supporting the

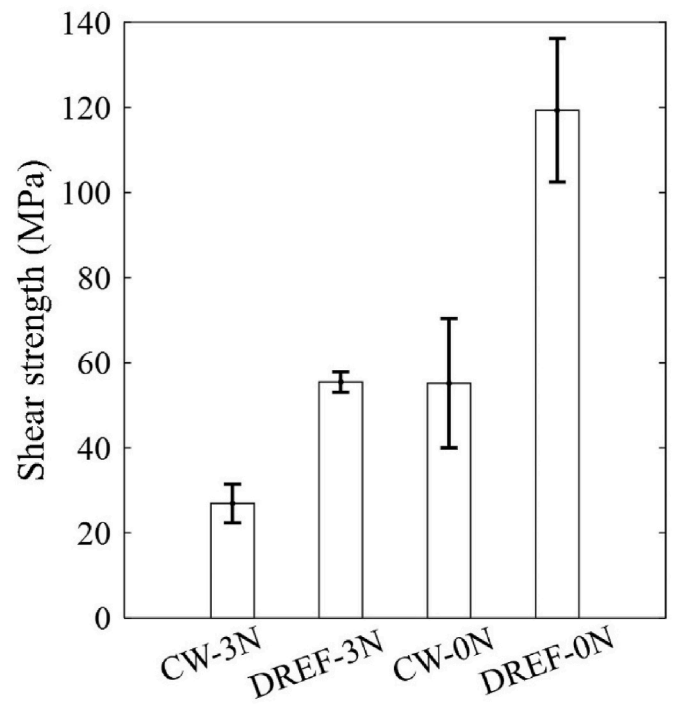


Fig. 12. Average measured in-plane shear strength of GF/PET rods for CW-3N, DREF-3N, CW-ON and DREF-ON.

literature's argument that in-plane shear strength decreases with increasing porosity [18,34]. DREF-ON demonstrated a 119.35 ± 16.89 MPa for in-plane shear strength, significantly exceeding those obtained in the other experiments. DREF yarns has the potential of producing superior performances in pultruded composite materials despite the absence of tension during pultrusion.

4. Conclusion

This study introduced the feasibility of thermoplastic pultrusion with DREF yarns, and proved more effective results when tension was not applied to the input material yarns. Composites rods were produced using a multi-die pultrusion system, where CW and DREF yarns were evaluated as input materials. DREF yarns' structure assessment highlighted a notable uniformity in the distribution of polymer and GF. Additionally, heat response assessment confirmed that continuous polymer fibres, similar to those present in CW yarns, have a tendency to shrink inducing the entanglement of GF. CW and DREF yarns were used to study the effect of yarn tension on sloughing, porosity, and mechanical properties of pultrudates. Yarn tension increased the occurrence of sloughing defects. Due to the compacted GF and the reduced permeability, a weak layer of polymer was formed on the exterior of the pultrudate that tore away from the pultruded composite after adhesion to the cooling die wall. DREF-ON had the least number of sloughing defects, with the actual diameter (4.63 ± 0.09 mm) being the closest to its diameter without sloughing (4.65 ± 0.01 mm). Additionally, yarn tension was shown to impact fibre volume fraction due to the presence of sloughing defects. In DREF-ON, v_f was measured at 56.0 ± 0.7 % and precisely matched the theoretical value ($v_{f,th}$) of 56 %. While evaluating porosity, the size of GF agglomeration and yarn tension indicated to be directly linked to void content of the pultrudate. DREF-ON exhibited the lowest v_v at 1.1 ± 0.1 %. Microscopic image of the cross-section of DREF-ON showed an insignificant amount of porosity and indicated that the structure of DREF yarns enabled achieving high impregnation without any application of tension during pultrusion. Moreover, CT scan images of pultrudates confirmed that the absence of yarn tension

induces fibre waviness in input materials with continuous thermoplastic fibres like CW yarns, while fibre waviness was absent in DREF yarns with discontinuous thermoplastic fibres, even without tension. DREF-ON surpassed the other experiments with an in-plane-shear strength of 119.35 ± 16.89 MPa. The results of the study highlighted the potential of thermoplastic pultruded composites manufactured using DREF yarns, particularly GF/PET rods. These rods could be suitable for use in structural components and automotive parts due to their strength and cost-effectiveness. Although the findings of this study were not affected by the choice of input materials with different types of GF, future work will involve using input materials with the same type of GF for further evaluation. Additionally, while no clear effect of the level of the standardized tensions applied on the overall pultrude quality could be found during this study, future investigations will be done to compare DREF and CW input materials with equivalent standardized tensions for consistency. In conclusion, DREF yarns present promising potential for use in thermoplastic pultrusion of high-performance composites across various fields, particularly due to their ability to limit fibre waviness even without tension. Future research will focus on accelerating the pultrusion speed while evaluating the pulling forces and the comparative impregnation behaviour of both materials. Additionally, efforts will be directed toward refining cooling processes to mitigate sloughing defects and work on enhancing the overall quality of composite profiles. Future studies will also investigate the impact of varying the nominal fibre volume content of the pultrude on sloughing defects to characterize their possible relationship. Nonetheless, this study paves the way for a broader utilization of DREF yarns as a pultrusion input material for commercial applications.

CRediT authorship contribution statement

Maissaloun El-Jakl: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Louis Laberge Lebel:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.compositesb.2024.111908>.

Data availability

Data will be made available on request.

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