JOURNAL OF THERMOPLASTIC COMPOSITE MATERIALS

Original Research Article

Microstructural and mechanical investigations regarding the formability of glass fiber reinforced thermoplastic pultruded profiles

Journal of Thermoplastic Composite Materials
2025, Vol. 0(0) 1–18

Article reuse guidelines:
sagepub.com/journals-permissions
DOI: 10.1177/08927057251412780
journals.sagepub.com/home/jtc
Sage

Joél Schukraft[1,2], Moritz Fünkner[3], Feiyun Zhang[3], Haoyang Liu[4], Michael Leander Wilhelm[3], Louis Kaptur[4], Frank Henning[3,4,5] and Andrew N Hrymak[1,4]

Abstract

Thermoplastic fiber reinforced composites have crucial benefits over thermoset composite materials regarding sustainability and reusability, as well as in post-processing, like welding or forming. In this study in-situ pultruded unidirectional reinforced glass fiber reinforced anionic polyamide composites are investigated for their formability, to be used as local stiffening elements in light weight over molded polymer matrix composites. A forming setup was designed and manufactured and a systematic study on forming parameters was carried out in a bending radius ranging from 10 to 30 mm, pre-heating temperature from 180 to 235°C and a fiber volume content from 60 to 70 vol -%. The formed profiles were investigated regarding their stiffness in a bridged apex flexure test and a cantilever flexure test and the microstructure of the composite with microscopy and computed tomography. The ideal forming parameters were found to be 20 mm bending radius, 70 vol.-% glass fiber content and 215°C pre-heating temperature of the profiles, for the forming setup used. For forming with lower radius and temperatures, the

[1]Department of Chemical and Biochemical Engineering, University of Western Ontario, London, ON, Canada
[2]Institute for Materials Resource Management, University of Augsburg, Augsburg, Germany
[3]Fraunhofer-Institut für Chemische Technologie ICT, Pfinztal, Germany
[4]Fraunhofer Innovation Platform for Composites Research, London, ON, Canada
[5]Institute of Vehicle System Technology, Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany

Corresponding author:
Joél Schukraft, Department of Chemical and Biochemical Engineering, University of Western Ontario1151 Richmond St. N., London, ON N6A 5B9, Canada.
Email: jschukra@uwo.ca

profiles showed fiber buckling, undulations and folded fiber bundles up to fiber breakage in the inner of the formed radius. For higher temperatures, degradation on the profile surface got visible and squeeze out effects, reducing the profile shape quality. This led to lower mechanical properties and higher scatter of values. The findings give insights to process optimization for forming thermoplastic pultrusion profiles and help to prevent pre-damage during manufacturing. With this, the study participates in making fiber reinforced polymer matrix composites more sustainable and in the green transformation of structural light-weight materials.

Keywords

Pultrusion, thermoplastic composites, GFRP, forming, CT investigation, mechanical testing

Introduction

Pultrusion is a continuous manufacturing process to produce fiber-reinforced polymer profiles with a consistent cross-sectional area. Pultruded profiles with thermoplastic matrix systems offers significant advantages over thermoset ones not only in recycling and sustainability,[1] but also in post-processing, such as injection molding/over molding,[2] ultrasonic welding,[3] and thermal forming.[4] Thermoplastics have a growing share in the composites market - 39% by 2022,[5] compared with thermosets. The cost index shows that thermoplastic components manufacturing can be more cost-effective than the processes with thermosets.[6]

Pultruded profiles usually have a high fiber volume fraction, resulting in excellent mechanical properties. This makes them well suited for load bearing structural components and for local reinforcement along the fiber direction in large or complex components (e.g. in LFT-D, injection molding or compression molding applications[7]). As a continuous process, pultrusion ensures high production efficiency and maintains consistent cross-sectional geometry and straightness. However, this consistency restricts the range of achievable shapes of the profiles. Pultruded profiles based on conventional thermoset resin systems (e.g., unsaturated polyester, epoxy, vinyl ester) lack postforming capability because they cannot be reshaped after the curing of matrix during the pultrusion process. Recent research increasingly focuses on the post-processing of pultruded profiles with thermoplastic matrices through thermoforming to enhance their functionality. By locally forming profiles where reinforcement is needed, we can reduce the number of parts used, material consumption, weight, and cost.

One of the key challenges in thermoforming is identifying the optimal combination of process parameters to achieve the desired shape without defects, including bending radius, processing temperature during the process, and the design of the forming tools. Meanwhile, the thermoformed profiles should maintain their mechanical properties while achieving the defined shape for subsequent processes.

The potential of pultruded profiles for thermoforming into complex shapes, other than flat bars, has been investigated. According to the review by Minchenkov,[8] pultrusion with thermoplastic matrix systems include two major approaches – non-reactive with melt-impregnation (PP, PA, PPS) and reactive with in-situ polymerization (PMMA, aPA6). Engel et al.[9] investigated the bending behavior of unidirectional glass fiber reinforced polypropylene (PP) tapes and found a correlation between heating temperature, forming velocity, and the resulting radius of the tapes. Zoller et al.[10] presented the results of reactive polymerization with an acrylic thermoplastic resin, Polymethyl methacrylate (PMMA, product name: ELIUM®), in a pultrusion process to manufacture continuous fiber-reinforced profiles. These profiles showed comparable mechanical properties as thermosets composites and the advantage of their post-formability for complex shapes due to its thermoplastic matrix.

McCool et al.[11] focused on carbon fiber reinforced thermoplastic composites with polyphenylene sulfide (PPS) and the critical process parameters for post-thermoforming process. Fiber volume fractions, bending radius, temperature, cycle time, and design of the bending tools are the key process parameters that will influence the results of the bent profiles. Inappropriate setting of parameters during the thermoforming process will cause failures like fiber buckling, wrinkling, and matrix cracking. This paper also proved that carbon fiber reinforced composites can also be thermoformed, since fibers themselves are flexible and have minimal impact on the consequence of the formability of pultruded profiles. Besides composites with thermoplastic matrix, the research of Aranberri et al.[12] proved that recyclable Vitrimer-based epoxy resin can be used in the pultrusion process. The pultruded profiles are also thermoformable.

An alternative to the post thermoforming process to produce non-flat composite profiles is the curved pultrusion.[13] To produce a large-scale structural part for pedestrian bridges, Liu et al.[14] developed the beam with the curved pultrusion process. In this research, the complex buckling behaviors of pultruded GFRP beams have been reviewed. Full-scale three-point bending tests on the proposed curved-pultruded profiles have been carried out to investigate failure modes, load-carrying capacities, and deformation of curved profiles. Guo et al.[15] expanded the perspective by investigating the hybrid structure of CFRP-Steel and its formability. This research highlights the higher forming precision of CFRP-steel hybrid structure than pure steel counterparts due to smaller spring-back effect.

Research on the formability of fiber-reinforced polymers has already focused on pre-consolidated laminates using PP material[9] and PPS material[11]; PMMA-based profiles produced by pultrusion with thermoplastic in-situ polymerization[10]; and pultruded profiles with Vitrimer-based epoxy systems.[12] However, systematic studies on the formability of pultruded profiles with aPA6 and the influencing factors are still yet to be carried out. Profiles manufactured by reactive pultrusion through anionic polymerization of ε-caprolactam to polyamide 6 (anionic PA6, aPA6) show high mechanical properties due to the high achievable fiber volume fraction and offer formability thanks to the thermoplastic matrix.

This study will investigate the feasibility of thermoforming pultruded profiles with thermoplastic aPA6 matrix, with glass fiber reinforcement at fiber volume fraction (FVF) of 70 vol. % and 60 vol. %. The pultruded profiles have a cross-sectional area of 20 × 2 mm, and were cut into the length of 160 mm. They will be bent to a 90° angle.

In this research, a thermoforming hardware system, including forming tool, heating system, and sensors, has been set up to carry out the trials with pultruded profiles. By varying fiber volume fraction, bending radius, forming temperature and holding time, the flat profiles have been bent with the thermoforming hardware according to the design of experiment (DoE). Then, cantilever flexure tests and bridged apex flexure tests were conducted to investigate the stiffness of the formed profiles and the strengthening effect and possible loss due to damage of the fibers in the composite material after the forming process. Furthermore, microscopy investigations on the surface of selected samples were carried out to investigate the fiber position and influence of the forming process. Finally, the factors influencing the mechanical properties of the profiles after the thermoforming process will be assessed. Also, the deformation and fiber behavior will be analyzed through microscopic investigation. Based on the results of this study, potential for further investigations and applications using thermoformed pultruded profiles are discussed.

This paper provides a systematic study on thermoforming pultruded profiles with anionic PA6 (aPA6) matrices, complementing the prior work on PP, PPS, PMMA and vitrimer based epoxy matrix systems. It demonstrates the feasibility of 90° bending of 20 × 2 mm pultruded GFRP-profiles with high fiber volume fractions (60%–70%). Mechanical tests (cantilever and bridged apex flexure) and microscopy analysis help evaluate the results in both quantitative and qualitative ways. Besides, the study delivers practical guidance for building a sensor-based thermoforming platform, tool design, and for a DoE varying FVF, bend radius, temperature, and hold time to map process windows.

Material and methods

For production of the glass fiber reinforced polyamide six profiles with a constant rectangular cross section of 20 mm × 2 mm, AP-Nylon® caprolactam flakes, sodium-caprolactamate catalyst (Bruggolen® C10), and hexamethylene-1,6-dicarbamoylcaprolactam (Bruggolen® C20P) by L. Brüggemann GmbH & Co. KG (Heilbronn, Germany) were used to form anionic polyamide 6 (aPA6) as the matrix material in the pultrusion process. For the unidirectional reinforcement of the profiles, Johns Manville StarRov® 2400-886 glass fiber rovings were utilized. Within known stable processing parameters, two profile variants were produced, differing only in their fiber volume fraction (FVF) of 70 vol. % and 60 vol. %, respectively. The profiles were cut into specimens with a length of 160 mm each.

Mechanical and thermal properties of profiles produced similarly are given in Table 1.

Special characteristics of reactively processed caprolactam are a significantly higher molecular weight with typical values of weight average molecular weights (M_W) of 300.000 g/mol–500.000 g/mol[16] and a higher degree of crystallinity compared to hydrolytically polymerized polyamide 6. The tensile modulus of neat polyamide six based on anionically polymerization is reported with approx. 3.2–3.4 GPa and typical tensile strength with 70–80 MPa.[17]

Table 1. Mechanical and thermal properties of profiles produced similarly to the one used in this study with a FVF of 69.7%.[16]

Properties	Unit	Profiles with FVF of 69.7%
Tensile strength 0°	MPa	1187 (σ = 25)
Tensile modulus 0°	GPa	56.5 (σ = 2.0)
Compression strength 0°	MPa	815 (σ = 90)
Compression modulus 0°	GPa	56.1 (σ = 1.7)
Bending strength 0°	MPa	1475 (σ = 55)
Bending modulus 0°	GPa	56.0 (σ = 0.4)
Shear strength 0°	MPa	66.9 (σ = 3.4)
T_G (DMA based on G′)	°C	68.6 (σ = 1.9)
Density	g/cm^3	2.147 (σ = 0.001)
Heat deflection temperature HDT-C	°C	191.6 (σ = 2.9)
Melting temperature T_S	°C	216.3 (σ = 0.7)

To investigate the formability of thermoplastic pultruded profiles, forming experiments at different bending radii, bending temperatures and fiber volume contents were carried out.

Forming tools

The forming tools represent a die bending setup and were made of aluminum for good thermal conductivity, fast cooling and are equipped with adapters to fit in an MTS Criterion C45_105E universal test system with an LPS.105 100 kN load cell. The design of the bending setup was chosen regarding the experience, gained in the Department of Chemical and Biochemical Engineering, University of Western Ontario, Fraunhofer-Institut für Chemische Technologie ICT and Fraunhofer Innovation Platform for Composites Research in collaboration in this field and part of an ongoing PhD project. Goal of the tool design was to keep the bending radius in a range flexible, by using adapters with removable inserts and to test a broad range of application-oriented geometries. The bending angle was set to 90° and the bending radii of the profiles were chosen to be 10 mm, 20 mm and 30 mm. For each bending radius, a separate forming die was designed and manufactured. The dies are intended to form 2 mm thick profiles. Therefore, the radius was set to +1 mm on the outer (concave) tool side and – 1 mm on the inner (convex) tool side. The design is shown representative in Figure 1 for the 10 mm radius die.

Forming setup

The composite material was heated in an IR field of one bottom and one top heater with a distance of 22 cm and 2 × 1500 W power supply in a pre-test. The surface temperature was measured for every heating time with a precise and fast reacting thermocouple with low

Figure 1. Forming tool with a 10 mm radius 90° bend and adapters for a universal testing machine. Lower half convex, upper half concave part.

heat capacity to keep the surface temperature as accurate as possible. An Anritsu Meter MG-11K-TS1-ANP thermocouple and a Testo 922 thermometer were used. The pretest results showed heating times in a range of 1:10 to 3:00 minutes show the full range from not fully molten matrix up to onset of degradation in the polymer matrix on the surface of the composite profiles and sagging of the profiles due to loss of stability by the fully molten matrix.

To complete the forming process, before the forming tools take the heat out of the surface of the matrix of the pultruded composite material and it freezes during the bending process, the forming tool setup was set up in a heat chamber and the temperature was set to 100°C. Preheating of the chamber with the fully mounted setup was minimum 1 h, so the whole set up was in a isothermal state.

Forming parameters

The used forming parameters are shown in the following, Table 2, with the respective nomenclature.

The preheated profiles were taken from the IR-field, after the heating time was completed and directly transferred into the open forming tool, which is placed in a heated chamber setup in the universal testing machine. The forming tool was closed displacement controlled to a minimum tool distance of approx. 2 mm. To apply the necessary consolidation pressure, the tool distance was set 20 µm below the original profile thickness. After the matrix of the profiles was fully solidified, the forming tool was opened and the formed profile taken out of the tempered tool @ 100°C after 1 minute. The parameter set PA6_70_30_235 was not taken into the design of experiment, as the higher bending radius was expected to have less critical forming conditions, like the pre-tests proved.

Characterization methods for the formed profiles

Stiffness of the formed profiles. To investigate the stiffness of the formed profiles and possible loss due to damage of the fibers in the composite material after the forming, two different tests were carried out.

First, a cantilever flexure test on the 90° bend profiles was carried out in the elastic range. One end of the sample was clamped, so that 50 mm of free length was kept of the profile to the center of the bend. From the center of the intersection of the straight profile sections another 50 mm were determined on the other side of the profile, and a bending pin

Table 2. Overview of the tests with varied testing parameters. For each parameter set minimum three samples were formed and tested.

Sample identification	Fiber volume content [vol.-%]	Bending radius (mm)	Bending temperature (°C)
PA6_70_10_180	70	10	180
PA6_70_10_205	70	10	205
PA6_70_10_215	70	10	215
PA6_70_10_235	70	10	235
PA6_70_20_180	70	20	180
PA6_70_20_205	70	20	205
PA6_70_20_215	70	20	215
PA6_70_20_235	70	20	235
PA6_70_30_180	70	30	180
PA6_70_30_205	70	30	205
PA6_70_30_215	70	30	215
PA6_60_10_180	60	10	180
PA6_60_10_215	60	10	215
PA6_60_20_215	60	20	215

was attached to carry out the test. A closer description of the setup can be found in Figure 2(a). The test was carried out displacement controlled based on ASTM D790 with a test speed of 2 mm/min, the modified span with of 50 mm form the center of the intersection of the straight profile sections and a maximum deflection of 5 mm.

Second, a bridged apex flexure test was carried out in the elastic range on the 90° bend profiles. Both ends of the sample were placed on a flat and polished, massive steel plate. Both straight profiles sections around the bend form a 45° angle with the steel plate. The bend section faced the top and was compressed with a polished flat compression stamp. A Preload of 1N was set and the test was also carried out with a test speed of 2 mm/min. The maximum displacement of the compression stamp was chosen to be 3 mm to stay in the elastic range of the material. More details can be taken from Figure 2(b).

To further investigate the fiber orientation and possible damage during forming next to the stiffness of the composite profiles, microscopy investigations were carried out.

Microscopy of the formed profiles. Microscopy investigations on the surface of selected samples were carried out with a Keyence VHX6000 microscope and different magnifications. A scale bar is given in every image in the results section.

In addition to the surface investigation and to avoid any influence from the destructive preparation method, computed tomography investigations have been carried out on six different samples, to investigate the fiber position and influence of the forming process.

The samples were scanned with a Zeiss Xradia 410 Versa computed tomography with a 0.4X Objective and a Zeiss LE2 filter at 65 kV and 165 µA, 25 s exposure time and 2401 images/360°. The sample source distance was set to 120 mm and the sample detector distance to 95 mm. The resulting voxel size is (19 µm)^3. Image processing was carried out with an Avizo 3D software by Thermofisher Scientific.

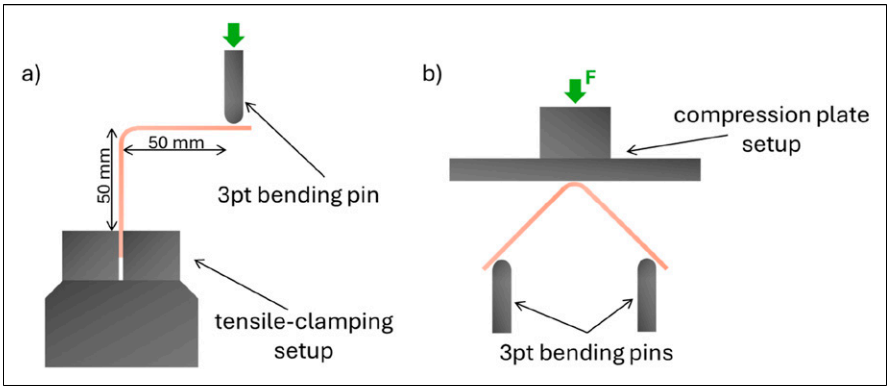

Figure 2. (a) Schematic cantilever flexure test set-up with a tensile clamping unit on the lower end and a three-point bending pin for loading the formed profile. (b) Schematic bridged apex flexure test with a holding concept for the ends of the profiles and a compression plate for loading the formed profile from the top.

Results

The influence of forming parameters was investigated systematically and the results for mechanical and microstructural investigations are presented in the following.

Mechanical investigations

From the cantilever flexure test in Figure 3, the bending profiles with 10 mm bending radius showed decreasing stiffness with increasing surface temperature, with the highest stiffness of 4.3 N/mm at 180°C and lowest stiffness of 3.8 N/mm at 235°C. For the bending profiles with 20 mm bending radius, the lower surface temperatures of 180°C and 205°C resulted in lower stiffness, and the higher surface temperatures of 215°C and 235°C resulted in higher stiffness.

At 180°C and 205°C, the profiles with 10 mm bending radius had higher stiffness than the ones with 20 mm bending radius. At 215°C and 235°C, the profiles with 20 mm bending radius had higher stiffness than the ones with 10 mm bending radius. The trend in stiffness is less clear for the samples with 30 mm bending radius, but showed an overall increase with increasing surface temperature.

From the bridged apex flexure test in Figure 4, the profiles with 10 mm bending radius showed increasing stiffness with increasing surface temperature up to 215°C, with the highest stiffness of 13.5 N/mm. At 235°C the stiffness drops and reaches only 12.5 N/mm. For the profiles with 20 mm bending radius, a clear trend is visible, and the lowest surface

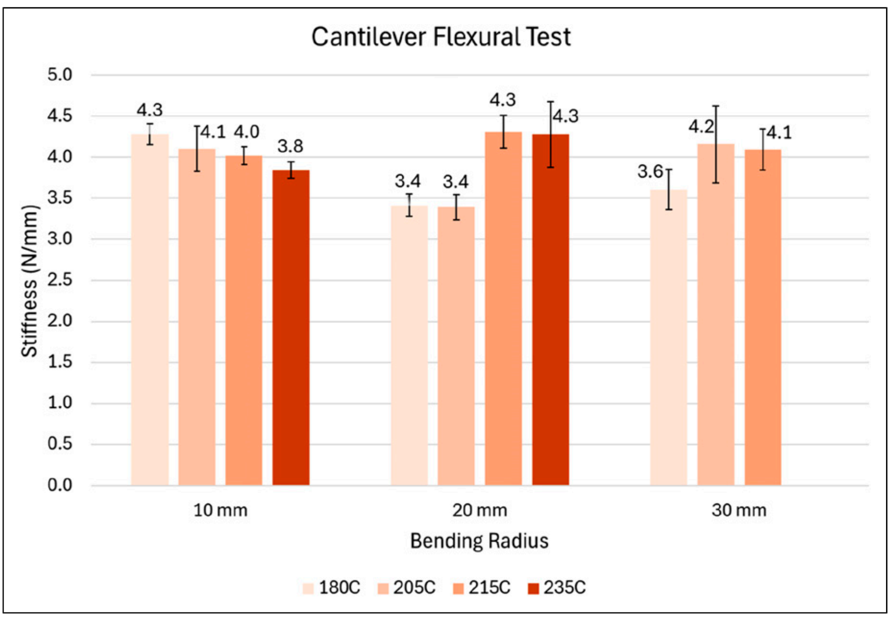

Figure 3. Cantilever flexure test results for 70% fiber volume content specimens.

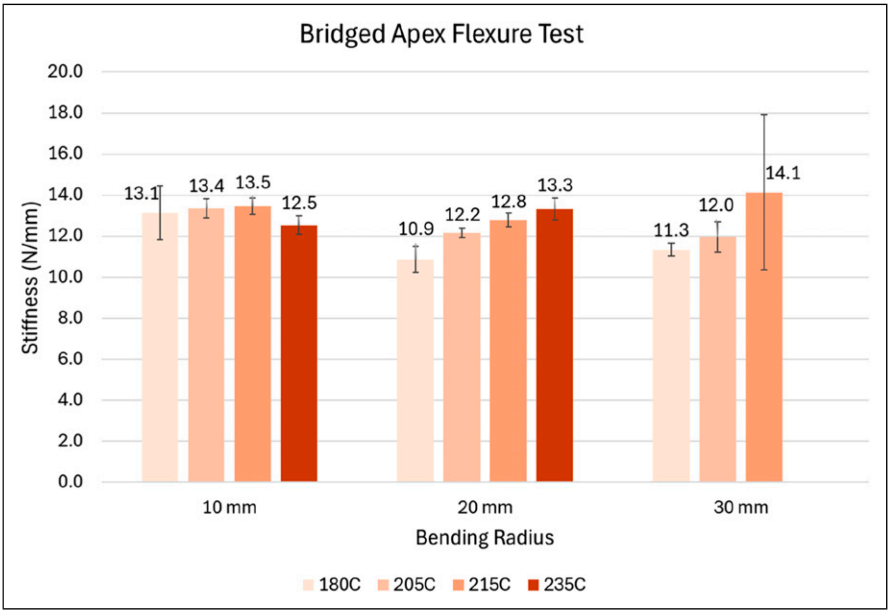

Figure 4. Bridged apex flexure test results for 70% fiber volume content specimens.

temperature resulted in the lowest stiffness, as higher surface temperatures resulted in higher stiffness. At 215°C, the profiles with 10 mm bending radius had comparable stiffness with the profiles with 20 mm bending radius at 235°C. The trend in stiffness is also observable for the 30 mm bending radius profiles but showed an increase of standard deviation with increasing surface temperature. The variation could be due to the different types or magnitudes of microstructural damage, which may be representative of the expected variation under prescribed forming conditions.

Microstructural investigation

Figures 5 and 6 show the computed tomography results of the microstructural investigations. For comparison, the bending radius, forming temperature, and fiber volume content are displayed regarding their impact on the forming process and the quality of the formed profiles.

In Figure 5 defects inside of the profiles are highlighted with colored arrows in two different sections of the profiles (ii) and iii). Cracks, voids – formed by fiber undulations - and surface imperfections due to fiber buckling are visible. The surface damage is mainly visible for the lower forming temperature and in the inner radius of the profile. Damage occurs also only inside of the profiles and at the smaller bending radius of 10 mm. For the 20 mm bending radius and 215°C forming temperature, no damage occurs and the impact on the inner radius surface quality is very little.

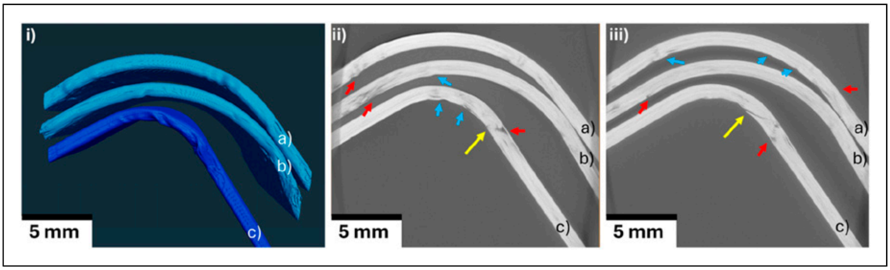

Figure 5. Computed tomography results of the 70 vol.% in comparison. (i) 3D image of the formed profiles, 20 mm bending radius in light blue (for (a) and b)) and 10 mm bending radius in dark blue (for c). (ii) and (iii) two cross-sections of the formed profiles, displayed in 3D in (i) - yellow arrows mark damage in the profiles, red arrows fiber undulation and blue arrows mark fiber buckling with impact to the surface quality. (a) 20 mm bending radius @ 180°C, (b) 20 mm bending radius @ 215°C, (c) 10 mm bending radius @ 180°C.

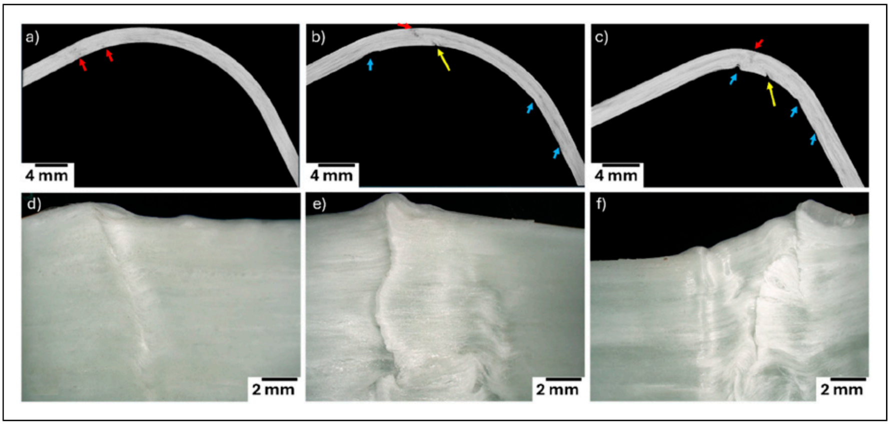

Figure 6. (a...c) Computed tomography results of the 70 vol.% and 60 vol.% in comparison. Cross sections of the formed profiles with 20 mm bending radius (a) and (b) and with 10 mm bending radius (c). Yellow arrows mark damage in the profiles, red arrows fiber undulation and blue arrows mark fiber buckling with impact to the surface quality. (d...f) Microscopy images of the inner radius surface for the respective profiles above. (a) and (d) 20 mm bending radius @ 235°C with 70 vol.%, (b) and (e) 20 mm bending radius @ 215°C with 60 vol.%, (c) and (f) 10 mm bending radius @ 180°C with 60 vol.% glass fiber content.

The impact of the fiber volume content can be observed in Figure 6, where a comparison between the highest forming temperature (235°C) with 70 vol-% fiber content, and two profiles with 60 vol-% fiber content (middle and right) is displayed. For the lower fiber volume content, damage occurs in the profiles at the same forming parameters, where no damage occurs in the 70 vol-% fiber content profiles. The microscopy images show fiber undulation and buckling on the surface. Damage by cracks longing into the inside of the profiles are formed by folded fiber bundles and breakage of the same due to very small bending radii. For figure e) in the lower center of the image a hole in the inner radius surface is visible, which indicates the impact of the lower fiber volume in the profile for the forming process and shows how the material is deformed during the forming process.

Discussion

Using the described setup, three different bending radii were investigated, and the preheating temperatures of the profiles were varied across at least three levels. Specimens from both the PA6_70_10… and PA6_70_20… series include one additional higher temperature setting.

A key observation from this setup and method was that no overbending was necessary to achieve the targeted 90° angle of the profiles. This finding correlates with the observation that there was almost no springback force present in any of the profiles after bending. Two potential explanations for the absence of significant springback forces can be proposed for a given bending radius. Firstly, the combination of temperature (which exceeded the typical crystallization temperature of 180°C in all cases, compare[18]), forming speed, and forming time could have been sufficient to allow for plastic deformation of the PA6 matrix and enable the glass fibers to reposition into a less tensioned state without breaking. Secondly, the forming parameters may not have been sufficient to achieve the desired plastic deformation, leading to localized damage in the profiles, such as fiber breakage or delamination. The three different bending radii should demonstrate a variation of difficulty in forming geometries, since for smaller bending radii the same total deformation must happen in a smaller area compared to larger bending radii. As only a local re-heating and forming in the profiles is carried out and no material is taken or added to the profile, the ratio between fibers and matrix is considered to be constant, also after the forming process.

The sufficiency of the forming parameters is further evaluated through two mechanical tests designed to assess the structural integrity and performance of the formed profiles under bending loads. It is assumed that more damage will occur on the inside radius of the bend since the glass fibers cannot resist the compression forces during bending and will eventually show undulations and misalignments according to their original position. Small undulations may already lead to a general decrease in stiffness for the bending area. An additional decrease in bending stiffness indicates potential further damage to the profiles due to insufficient forming parameters. On the outside radius, the fibers are put under tension during the bending procedure, likely being able to withstand the tensile forces and remaining intact and in their original orientation.

The cantilever flexure test investigates the profiles under a closed bend, where the outside radius is put under tension while the inside radius is compressed. In contrast, the bridged apex flexure test examines an open bend, applying a compression load on the outside radius while the inside radius experiences a tensile load. By conducting both tests, it is possible to evaluate the inside radius of the bend, where most damage is expected due to insufficient forming parameters, in terms of both compressive and tensile properties.

Additionally, CT scans will be utilized to provide detailed insights into material behavior, revealing internal structures and potential defects that may not be detected through mechanical testing alone.

The sometimes-high deviations in the mechanical test results could be attributed to the fact that the profiles were not additionally fixed within the forming die. This has resulted in some profiles to form the bend not exactly in the middle of the profile but starting the bend somewhere close to the middle and then aligning with the apex of the forming die afterwards, causing a lateral shift. This was especially noticeable with the high preheating temperature of 235°C. A reduction in total specimen and investigated configurations was unfortunately necessary due to a limited amount of initially flat pultrusion profiles available.

The 20 mm setup represents the midpoint for the bending radius parameter, and the advantages of increased softness at this radius are reflected in the results of the mechanical tests. For the cantilever flexural test, two distinct levels in stiffness can be observed. This suggests that a sudden change in deformation mechanisms leads to less fiber undulation and buckling within the profile, significantly improving compression properties in the inside radius, while reaching an optimum in stiffness for temperatures above 215°C. The observed linear increase in stiffness with higher forming temperatures in the bridged apex flexure test can be attributed to a gradually improved alignment of the fibers relative to their original 0° orientation, enhancing reinforcement under load conditions. This trend is supported by the CT scans, which show fewer areas of fiber buckling and undulations at a forming temperature of 235°C (Figure 6(a)) and 215°C (Figure 5(b)) compared to 180°C (Figure 5(a)) while keeping other parameters constant.

This general trend is also evident in both tests for the 30 mm bending radius. The sudden increase in stiffness in the cantilever flexure test occurs at a lower temperature setting compared to the 20 mm bending radius. This could indicate a similar behavior in deformation mechanisms happening at a lower temperature. It is important to note that the deviations between specimens are larger compared to the 20 mm radius setup, and the 235°C preheating setting was not investigated. For the 10 mm bending radius setup, this trend is only partially confirmed. In the bridged apex flexure test, higher preheating temperatures initially exhibit a slight increase in stiffness. This test method reinforces the hypothesis of decreased damage at higher temperatures, as potential cracks on the inner radius, where they are most expected, would be further opened under tension. The observation that more damage and cracks appear as the bending radius is reduced is evident when comparing the CT scans of the 20 mm and 10 mm radius samples, both preheated at 180°C (illustrated in Figure 5(iii)). Consequently, an increase in stiffness with higher forming temperatures indicates less damage or cracking in the bending area, likely attributed to lower matrix viscosity. However, at a forming temperature of 235°C, an unexpected decrease in stiffness is observed, presumed to occur due to the profile squeezing out to the sides as the matrix viscosity becomes excessively low. When the matrix is too soft, the die design allows the fibers and matrix to squeeze out laterally, resulting in a reduction of profile thickness and consequently a loss of geometric bending stiffness. At this point, the negative effects of lateral squeezing are assumed to outweigh the advantages of reduced damage due to higher forming temperatures, which may explain the unexpected loss in stiffness.

In the cantilever flexural test for the 10 mm bending radius profiles, a clear decrease in stiffness is noted with increasing forming temperatures. This trend supports the theory of stiffness loss due to lateral squeezing of the profiles and increased side undulations resulting from excessively low matrix viscosity. The anticipated effect of reduced profile damage due to higher forming temperatures is less pronounced in this test, as the method tends to close potential cracks on the inner radius. Consequently, the negative impact of the squeezing-out effect is more significant.

Comparing Figure 5(b) with Figure 6(b), a reduction of the fiber volume content (FVC) to 60% leads to more damage in the profile while keeping other forming parameters constant. For the forming parameters of a 10 mm radius and 180°C preheating temperature, there is also more damage visible for the 60% FVC profiles compared to the 70% FVC profiles (see Figure 5(c) and 6(c)). Because of this, a lower FVC is seen as negative for this forming setup. This can be explained by the fact that a lower FVC directly correlates to a higher matrix content. During forming, the fibers are more likely to buckle or even fold over, as there is more preheated and soft matrix that gives way. If the fiber volume content is higher, there is less space for the fibers to fold over, as they support themselves and act as a boundary.

Generally, it was found that the bending radius significantly influences the forming effects. The same total deformation, in terms of the bending angle, must take place over a smaller area, resulting in higher localized deformations for smaller radii. Consequently, for identical forming parameters, increased damage and fiber undulations were observed at smaller bending radii. Therefore, preheating temperatures should be chosen separately for different bending radii, as a change in forming mechanisms and effects - especially for the smaller 10 mm bending radius compared to the 20 mm radius - was demonstrated.

In comparison with literature, this study fills a gap on the topic of thermoforming high fiber content thermoplastic pultruded flat profiles as a post-processing step. One study investigated the bending of thermoplastic round bars made from glass fiber reinforced polypropylene prepreg tapes achieving a fiber content of 33 vol%. It was shown that the fibers on the inner side of the bend were also undulated and likely caused a loss in mechanical properties in the form of a premature tensile failure. The strength degradation was mainly attributed to matrix cracks and delaminations.[19] However, in this study, suitable forming parameters have effectively reduced matrix cracks and delaminations, thus indicating the potential of optimizing the bending temperature and bending geometry as well as the importance of a high fiber volume content. Other Studies have been done on the thermoforming of fabric-reinforced thermoplastic laminates.[11,20] These thermoplastic laminates usually have lower fiber content compared to thermoplastic pultruded profiles (50 vol% compared to 60 vol% or more). Due to the high fiber content and the unidirectional fiber orientation, thermoplastic pultruded profiles possess high stiffness and can be more suitable as reinforcement than thermoplastic laminates depending on the application. The fabrics with fibers oriented in multiple directions also restrict the movement of fibers and flow of resin in some capacity during the thermoforming process, making thermoplastic laminates more dimensionally stable. In contrast, the unidirectional arrangement of fibers makes thermoplastic pultruded profiles more susceptible to lateral flattening due to resin and fiber movement under heat and pressure during the thermoforming process, which was explored in this study. Studies have also been conducted on producing curved profiles during the pultrusion process instead of during post-processing. This is usually achieved in thermoset pultruded profiles by pulling the resin-saturated rovings through a die at room temperature to form desired cross-sectional shape, then introducing the curvature and curing the resin through UV light after the die.[21,22] However, this technique is usually constrained to form simple round curvatures with relatively large radii, and not suitable for forming sharp geometries such as the ones explored in this study. The abilities of an epoxy vitrimer pultruded profile and a reactive acrylic thermoplastic pultruded profile to be thermoformed were studied, but the studies focused on the proof-of-concept instead of investigating the effects of processing parameters on the quality of the thermoformed part.

The successful thermoforming of PA6 pultruded profiles to create bent profiles in this study creates additional avenues for thermoplastic pultruded profiles to be used as structural reinforcement through overmolding in various applications. The ability to form the thermoplastic pultruded profiles into different geometries during post-processing enables them to be overmolded or inserted into sections with complex geometry and also needing reinforcement, which would not be possible with straight pultruded profiles. The use of thermoplastic resin material also enables better bonding between the pultruded profile and the overmolded part when they share the same resin system. Under intimate contact, the polymer chains would be able to diffuse across the interface through autohesion, further improving the mechanical performance of the overall part.[23] Thermoplastic pultruded profiles that combine dry fibers and resin during the process are also more cost effective than continuous fiber reinforced thermoplastic laminates, enabling reinforcement and overmolding applications that would not otherwise be cost effective. A major advantage of using thermoplastic resin instead of traditional thermoset resin in the pultrusion process is that it creates opportunities for recycling, as thermoplastics can be heated and reprocessed while thermosets cannot be reprocessed once cured. This ability to be melted and reshaped makes thermoplastic pultruded profiles an attractive solution in a sustainability-focused environment. It is worth noting that this study only investigated the bending of flat bar profiles. Round profiles are another common shape produced through pultrusion, and the bending of round profiles requires separate investigations to study the effects and the means of preserving the properties.[24]

Conclusion

This study successfully explored the formability of thermoplastic pultruded profiles, specifically focusing on profiles made from anionic polyamide six reinforced with glass fibers. Key findings indicate that both the bending radius and preheating temperature significantly influence the mechanical properties and structural integrity of the formed profiles. By increasing the forming temperature from 205 to 215°C, the profile stiffness could be improved over 25% in the cantilever flexural test for a 20 mm profile. The sensitivity of the narrow process window correlates with the microstructural integrity of the profiles.

The results demonstrate that optimized forming parameters can minimize damage in the profiles and maintain the desired mechanical performance. Notably, higher preheating temperatures generally improve stiffness of the profile after forming by allowing a higher fiber orientation in a lower viscous matrix during the forming process, while smaller bending radii lead to increased localized deformations and potential damage, as the difference in path length from the outer to the inner radius is concentrated locally, forming damage and changing the fiber orientation of the unidirectional reinforced profiles. A high fiber volume content of 70% helps minimize damage in terms of fiber folding, compared to the 60 % fiber volume content. The combination of mechanical testing and computed tomography provides a comprehensive understanding of the material behavior during the thermoforming process.

These insights underscore the potential of thermoplastic pultruded profiles for various applications, particularly in structural reinforcement where complex geometries are required. This could represent a cheaper alternative for co- or overmolding parts, where UD-tapes are the state-of-art continuous fiber reinforcement.

Acknowledgements

The financial support of the German Research Foundation (DFG) within the project 550315066 is gratefully acknowledged. We want to thank Surface Science Western, especially Ivan Barker for the support and the access to the X-ray micro Computed Tomography, founded by the Canadian Foundation for Innovation – 2017 Innovation Found (CFI-IF # 35961), Ontario Research Fund. We want to thank Johns Manville for the supply of glass fiber material. We want to thank Keith Ruck for his support in carrying out the mechanical tests, and the forming of the profiles.

Declaration of conflicting interests

The authors declare that there are no conflicts of interest related to this work.

Funding

The authors disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: This work was supported by the Deutsche Forschungsgemeinschaft (550315066), Ontario Research Foundation (CFI-IF # 35961).

Ethical considerations

The authors affirm that this research was conducted in accordance with ethical standards applicable to scientific investigations.

Consent to participate

No human participants, animals, or sensitive personal data were involved in the study.

Consent for publication

This study does not involve any individual person's data in any form (including individual details, images, or videos), and therefore, consent for publication is not applicable.

ORCID iD

Joél Schukraft https://orcid.org/0000-0002-4955-152X

Data Availability Statement

The data supporting the findings of this study are part of an ongoing research project and are not publicly available at this time. Access to the data is restricted to preserve the integrity of the study and ensure compliance with institutional and project-specific guidelines. The authors will consider reasonable requests for data access once the study is complete and the data have been fully validated.

References

1. Rybicka J, Tiwari A and Leeke GA. Technology readiness level assessment of composites recycling technologies. *J Clean Prod* 2016; 112: 1001–1012.
2. Paramasivam A. Investigating the failure behavior of over-molded thermoplastic composites: experimental testing and numerical modelling. *Appl Compos Mater* 2025; 32(4): 1659–1687.
3. Bose S, Chelladurai H and Ponappa K. A review on recent developments in ultrasonic welding of polymers and polymeric composites. *Weld World* 2024; 68(7): 1881–1903.
4. Benmokrane B, Mousa S, Mohamed K, et al. Physical, mechanical, and durability characteristics of newly developed thermoplastic GFRP bars for reinforcing concrete structures. *Constr Build Mater* 2021; 276: 122200.
5. Wilhelm ML, Kummert HH, Suratkar AP, et al. A study on the mechanical recycling of continuous glass fibre reinforced nylon 6 profiles produced by in-situ pultrusion. 2023.
6. JEC observer overview of the global composites market 2022-2027. 2023.
7. Qureshi J. A review of fibre reinforced polymer structures. *Fibers* 2022; 10(3): 27.
8. Minchenkov K, Vedernikov A, Safonov A, et al. Thermoplastic pultrusion: a review. *Polymers* 2021; 13(2): 180.
9. Engel B, Soemer E and Bocking J. Bending of unidirectional reinforced thermoplastics. In: *58th Ilmenau Scientific*. Colloquium, 2014.
10. Zoller A, Escalé P and Gérard P. Pultrusion of bendable continuous fibers reinforced composites with reactive acrylic thermoplastic ELIUM® resin. *Front Mater*. 2019; 6: 290. doi:10.3389/fmats.2019.00290.
11. McCool R, Murphy A, Wilson R, et al. Thermoforming carbon fibre-reinforced thermoplastic composites. *Proc Inst Mech Eng Part L* 2012; 226(2): 91–102.
12. Aranberri I, Landa M, Elorza E, et al. Thermoformable and recyclable CFRP pultruded profile manufactured from an epoxy vitrimer. *Polym Test* 2021; 93: 106931.
13. Talabi SI, Tobin J, Strom B, et al. Recent and future developments in pultrusion technology with consideration for curved geometries: a review. *Compos B Eng* 2024; 283: 111678.
14. Liu TQ, Feng P, Wu Y, et al. Developing an innovative curved-pultruded large-scale GFRP arch beam. *Compos Struct* 2021; 256: 113111.

15. Guo Y, Zhai C, Li F, et al. Formability, defects and strengthening effect of steel/CFRP structures fabricated by using the differential temperature forming process. *Compos Struct* 2019; 216: 32–38.
16. Wilhelm ML. Verfahrensentwicklung für die Herstellung kontinuierlich faserverstärkter, thermoplastischer Profile im Pultrusionsverfahren mittels in-situ Polymerisation von ε-Caprolactam. 2025. https://doi.org/10.3390/jcs4010007
17. Wilhelm M, Wendel R, Aust M, et al. Compensation of water influence on anionic polymerization of ε-Caprolactam: 1. Chemistry and experiments. *J Compos Sci* 2020; 4(1): 7.
18. Cho BG, McCarthy SP, Fanucci JP, et al. Fiber reinforced nylon-6 composites produced by the reaction injection pultrusion process. *Polym Compos* 1996; 17(5): 673–681.
19. Xian G, Zhou P, Bai Y, et al. Design, preparation and mechanical properties of novel glass fiber reinforced polypropylene bending bars. *Constr Build Mater* 2024; 429: 136455.
20. Limaye M, Pradeep SA, Kothari A, et al. Thermoforming process effects on structural performance of carbon fiber reinforced thermoplastic composite parts through a manufacturing to response pathway. *Compos B Eng* 2022; 235: 109728.
21. Britnell DJ, Tucker N, Smith GF, et al. Bent pultrusion—a method for the manufacture of pultrudate with controlled variation in curvature. *J Mater Process Technol* 2003; 138(1–3): 311–315.
22. Tena I, Sarrionandia M, Torre J, et al. The effect of process parameters on ultraviolet cured out of die bent pultrusion process. *Compos B Eng* 2016; 89: 9–17.
23. Akkerman R, Bouwman M and Wijskamp S. Analysis of the thermoplastic composite overmolding process: interface strength. *Front Mater* 2020; 7: 27.
24. Duchamp B and Zoller A. Pultrusion of bendable rebars based on a glass fibre reinforced thermoplastic. *JEC Compos*.