Continuous (recycled) fiber-filaments printed in large-scale additive manufacturing

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ABSTRACT

Large-scale additive manufacturing (LSAM) of continuous fibre-reinforced thermoplastics offers significant potential for lightweight aerospace structures but remains limited by sustainable feedstock availability and restricted deposition strategies.

This work presents an integrated manufacturing approach combining the development of continuous 12K carbon fibre filaments manufactured from both virgin carbon fibres and recycled fibres originating from industrial production waste with advanced deposition strategies for uninterrupted structural additive manufacturing. High-performance thermoplastic matrices, including polyphenylene sulfide (PPS) and polyaryletherketone (PAEK), were processed using a co-extrusion process to produce continuous fibre filaments suitable for LSAM. Their processability, microstructure, and mechanical performance were evaluated to assess the suitability of recycled fibres for structural applications.

In addition, localized trajectory adaptations for continuous fibre crossings and support-free three-dimensional deposition strategies were developed and experimentally validated using representative demonstrator structures.

The results demonstrate that recycled continuous fibre feedstocks can be successfully combined with advanced toolpath strategies, preserving continuous load paths while extending the geometric design space of large-scale additive manufacturing.

The presented approach provides a promising pathway towards sustainable, load-path-oriented composite structures for future aerospace and space applications.

1. INTRODUCTION

The increasing demand for lightweight, resource-efficient and mission-adapted structures continues to drive the development of advanced manufacturing technologies for aerospace and space applications. Besides achieving high specific mechanical properties, future manufacturing processes must enable rapid design adaptation, efficient material utilisation and economically viable production of highly individualised structural components. Large-scale additive manufacturing (LSAM) has therefore emerged as a promising technology, combining the geometric freedom of additive manufacturing with the processing of engineering thermoplastics and fibre-reinforced composite materials. Compared with conventional manufacturing technologies, LSAM enables the direct fabrication of large and highly customised structures while significantly reducing tooling effort and material waste [1].

Among the various reinforcement concepts, continuous carbon fibres offer the greatest potential for enhancing the mechanical performance of additively manufactured thermoplastic structures. In contrast to short-fibre reinforced polymers, continuous fibres provide uninterrupted load paths that enable efficient stress transfer along the fibre direction, resulting in substantially increased stiffness, strength and damage tolerance. Consequently, continuous fibre reinforced additive manufacturing has attracted considerable attention for structural aerospace applications, where lightweight design and load-path-oriented reinforcement concepts are of central importance [2-4].

Despite these advantages, current continuous fibre additive manufacturing technologies still exhibit several fundamental limitations. Most existing systems remain restricted to planar layer-by-layer deposition, limiting the fabrication of spatial reinforcement architectures that efficiently follow three-dimensional load paths. Furthermore, intersecting toolpaths generally require interruption of the continuous reinforcement, introducing discontinuities that reduce structural efficiency. In addition, support-free deposition of spatial reinforcement structures remains a major

technological challenge [3,4].
Besides these process-related limitations, sustainability has become an equally important challenge for future composite manufacturing. Carbon fibre production is associated with high energy consumption and considerable material losses during industrial processing. Continuous fibre production waste is frequently discarded because local defects prevent its use in conventional high-performance laminate manufacturing, although a large proportion of the intrinsic mechanical properties of the fibres remains unaffected. Preserving these continuous fibres for structural applications therefore represents an attractive opportunity to improve resource efficiency while simultaneously reducing the environmental footprint of composite manufacturing [5].
Previous work at the German Aerospace Center (DLR) established a co-extrusion process for manufacturing continuous fibre thermoplastic filaments from both virgin and recycled 12K carbon fibre tows. These investigations demonstrated the feasibility of producing printable continuous fibre filaments based on high-performance thermoplastics and provided the technological foundation for recycled continuous fibre feedstocks in large-scale additive manufacturing [6,7]. Building upon these developments, further advances are required to fully exploit the structural potential of continuous fibre LSAM. In particular, reliable processing of recycled feedstocks, uninterrupted fibre deposition across intersecting toolpaths and support-free three-dimensional deposition remain key challenges for manufacturing highly load-adapted composite structures.
To address these challenges, this work presents an integrated manufacturing framework combining sustainable feedstock development with advanced deposition strategies for continuous fibre large-scale additive manufacturing. Continuous fibre filaments manufactured from virgin and recycled carbon fibre tows are comparatively evaluated regarding processability, microstructure and structural performance. Building upon these feedstocks, localized toolpath adaptations enabling uninterrupted fibre crossings and support-free spatial deposition strategies are developed and experimentally validated using representative demonstrator structures. The overall workflow of the presented research is illustrated in Figure 1. It highlights the two main contributions of this work: (i) the development of sustainable continuous fibre filaments from recycled carbon fibre production waste and (ii) the development of advanced deposition strategies for uninterrupted, load-path-oriented large-scale additive manufacturing. By combining these complementary developments within a single manufacturing framework, the presented approach extends both the material basis and the geometric design space of continuous fibre large-scale additive manufacturing for future aerospace and space structures.

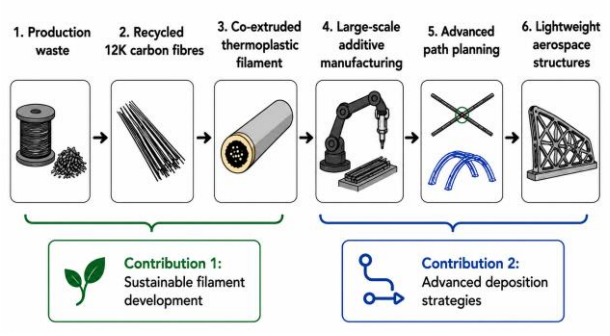

Figure 1: Overview of the presented workflow illustrating the two main contributions of this work: (1) the development of sustainable continuous fibre filaments from recycled carbon fibre production waste and (2) advanced deposition strategies for uninterrupted large-scale additive manufacturing of lightweight aerospace structures.

2. MATERIALS AND EXPERIMENTAL METHODS

This chapter describes the materials, filament manufacturing process, large-scale additive manufacturing system, and experimental procedures employed throughout this study. The experimental programme comprised the development and characterization of continuous fibre thermoplastic filaments manufactured from both virgin and recycled carbon fibres, followed by the experimental validation of advanced deposition strategies for uninterrupted continuous fibre placement and support-free three-dimensional printing. The overall methodology is structured to evaluate both the suitability of recycled continuous fibre feedstocks for structural large-scale additive manufacturing and the feasibility of the proposed process innovations.

2.1 Raw Materials

Two continuous carbon fibre reinforcement systems were investigated: a commercial 12K virgin carbon fibre tow and a recycled 12K carbon fibre tow recovered from industrial production waste. In contrast to conventional recycling approaches based on discontinuous fibres, the original continuous fibre architecture was preserved, enabling the recycled material to be processed directly as continuous reinforcement for extrusion-based additive manufacturing.
Three continuous fibre reinforced filament systems were investigated throughout this study. Two filament systems were manufactured at DLR using the ENDLOS-Effekt co-extrusion process and polyphenylene sulfide (PPS) as matrix material, reinforced with either virgin or recycled continuous carbon fibres. In addition to the in-house manufactured filament, a commercially available continuous carbon fibre reinforced polyaryletherketone (PAEK) filament was included

in the printing experiments as a reference material. All three filament systems were processed using the same large-scale additive manufacturing platform to evaluate the developed deposition strategies under comparable processing conditions. An overview of the investigated material systems is provided in Table 1.

Table 1: used material systems

Mat.-Sys-	Reinforc.	Matrix	Application
Dev. filament	Virgin continuous carbon fibre (12K)-AS7	PPS	Filament character. and printing
Dev. filament	Recycled continuous carbon fibre (12K)-T700	PPS	Filament character. and printing
Com. filament	Continuous carbon fibre	PAEK	Printing experiments

2.2 Continuous Fibre Filament Manufacturing

Continuous fibre reinforced thermoplastic filaments were manufactured using the DLR ENDLOS-Effekt co-extrusion process, which was developed for the continuous production of structural composite filaments for large-scale additive manufacturing [6,7]. The process integrates continuous fibre impregnation, filament consolidation, dimensional calibration and spool winding within a single continuous manufacturing route, resulting in printable composite feedstocks with homogeneous fibre distribution and stable filament geometry.

A major challenge in manufacturing continuous fibre thermoplastic filaments is the impregnation of densely packed carbon fibre bundles with highly viscous engineering thermoplastics. Since only a limited residence time is available within the processing zone, sufficient matrix infiltration must be achieved while maintaining continuous fibre alignment and a constant filament geometry. The resulting impregnation quality directly influences filament handling, extrusion stability and the mechanical performance of the printed components [7].

During manufacturing, the continuous carbon fibre tow is guided through the co-extrusion die, where the molten thermoplastic matrix is introduced under controlled thermal conditions. Ultrasonic excitation is applied within the impregnation zone to improve matrix infiltration and enhance process stability during continuous production [7]. After impregnation, the composite strand passes through a consolidation and cooling section before being calibrated to the target filament diameter and wound onto spools for subsequent additive manufacturing experiments. A schematic illustration of the manufacturing process is shown in Figure 2.

Both virgin and recycled 12K carbon fibre tows were processed using the same manufacturing route. Although the recycled fibres exhibited minor local variations resulting from their previous industrial processing history, only small adjustments to the fibre guidance were required. No modifications of the underlying co-extrusion concept were necessary, demonstrating the compatibility of recycled continuous carbon fibre production waste with the established filament manufacturing process.

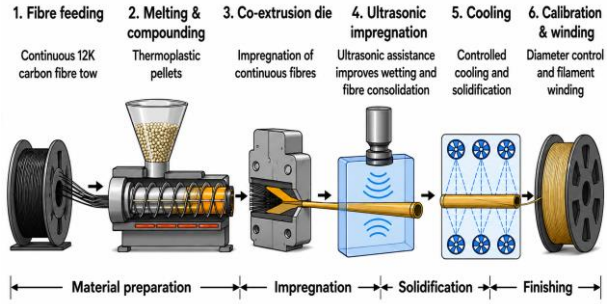

Figure 2: Schematic illustration of the DLR co-extrusion process for manufacturing continuous fibre thermoplastic filaments.

2.3 Large-Scale Additive Manufacturing System

Printing experiments were performed using a custom-developed large-scale additive manufacturing (LSAM) platform equipped with a high-temperature extrusion unit specifically designed for processing continuous fibre reinforced thermoplastic filaments. The system comprises a six-axis industrial robot, a heated extrusion unit and a temperature-controlled build platform to ensure reliable processing of high-performance thermoplastic materials.

The print head was developed to process continuous fibre reinforced filaments while maintaining homogeneous heating of the thermoplastic matrix and minimizing mechanical loading of the continuous fibre bundle during feeding. Stable processing requires a balanced interaction between material feed, extrusion rate and machine motion, as variations in fibre tension directly affect strand geometry, deposition accuracy and fibre alignment.

All printing experiments were performed using the same manufacturing platform. Process parameters, including nozzle temperature, printing speed and layer height, were adapted to the respective filament system and experimental objective. The investigated parameter ranges are summarized in Table 2. The parameter ranges cover all experimental investigations presented in this work and were adapted to the respective material system and demonstrator geometry.

Figure 3 shows the robotic LSAM platform used for the experimental investigations, while Figure 4 illustrates the custom-developed continuous fibre print head during the processing of continuous fibre reinforced thermoplastic filaments.

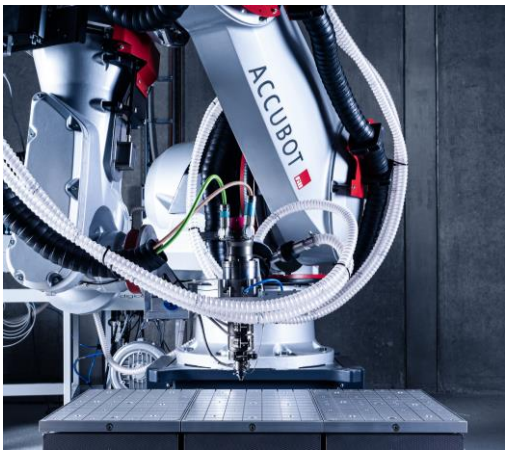

Figure 3. Experimental setup consisting of the robotic LSAM system

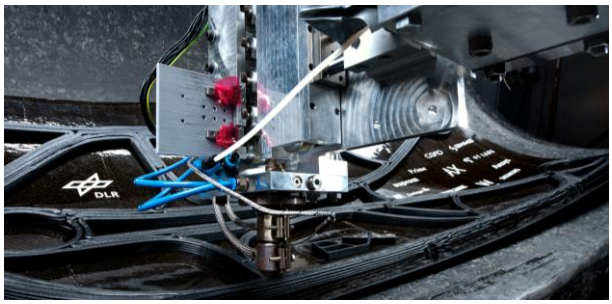

Figure 4. The custom-developed continuous fiber print head printing continuous CF/PAEK filament

Table 2: Parametersetup

Parameter	Value
Fibre	Virgin CF/ recycled CF
Matrix	PPS /PAEK
Filament diameter	1.2 mm
Nozzle diameter	1.3 mm
Nozzle temperature	350°C-490°C
Printing speed	30 – 3000 mm/min
Layer height	0.5 mm
Notch height	0.25 mm
Inclination angle	30° -90°

2.4 Experimental Methods

The experimental programme comprised both feedstock characterization and process validation experiments. Initially, the developed continuous fibre filaments were characterized with respect to their manufacturing quality, microstructure and mechanical performance. Optical microscopy was employed to evaluate fibre distribution and impregnation quality. Mechanical characterization was performed by tensile testing using a test procedure adapted from ASTM D638 [8]. A minimum of five specimens was tested for each material condition to compare the mechanical performance of filaments manufactured from virgin and recycled continuous carbon fibres.
Subsequently, the developed deposition strategies were investigated using representative demonstrator geometries addressing three key challenges of continuous fibre large-scale additive manufacturing. First, continuous fibre crossings were analysed to evaluate localized toolpath modifications designed to reduce material accumulation while preserving uninterrupted fibre continuity. Second, infrared thermography was employed to identify suitable thermal process windows for support-free deposition. Finally, progressively more complex demonstrator structures, including standing triangles, pyramid geometries and spatial lattice structures, were manufactured to validate uninterrupted free-space deposition under representative processing conditions.
The overall experimental workflow is illustrated in Figure 5.

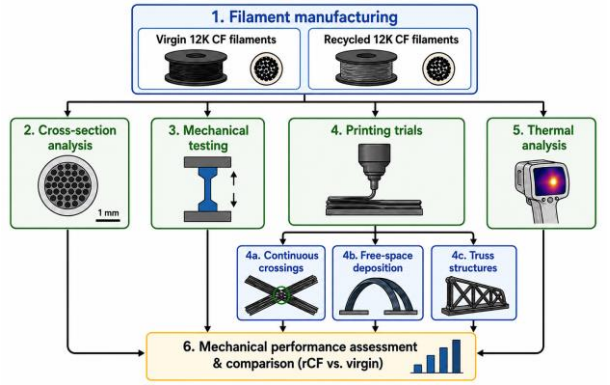

Figure 5: Overview of the experimental methodology employed for filament characterization and continuous fibre deposition investigations.

3. DEVELOPMENT AND CHARACTERIZATION OF CONTINUOUS FIBRE FILAMENTS

The successful implementation of continuous fibre reinforced large-scale additive manufacturing depends fundamentally on the quality of the employed feedstock material. Besides providing high mechanical performance, continuous fibre reinforced filaments must exhibit homogeneous fibre impregnation, stable geometry and reliable feeding behaviour during extrusion. Consequently, the development of robust filament feedstocks represents a prerequisite for the advanced deposition strategies presented in the following sections.
To evaluate the suitability of recycled continuous carbon fibres for structural additive manufacturing, continuous fibre reinforced PPS filaments were manufactured. The resulting filaments were subsequently characterized with respect to their manufacturing quality, microstructure and mechanical performance.

3.1 Filament Manufacturing

Continuous fibre reinforced thermoplastic filaments were successfully manufactured from both virgin and recycled 12K carbon fibre tows using the DLR ENDLOS-Effekt co-extrusion process described in

previous work [6,7]. Stable processing conditions were achieved throughout the manufacturing campaign, enabling continuous filament production without significant interruptions, fibre breakage or filament collapse. The manufactured filaments exhibited sufficient flexibility for spool winding while maintaining the stiffness required for reliable feeding during large-scale additive manufacturing.
Although the same manufacturing principle was applied to both fibre systems, slight differences in handling behaviour were observed. Owing to their previous industrial processing history, the recycled fibre bundles exhibited locally varying bundle morphologies, requiring minor adjustments to the fibre guiding system during manufacturing. These adaptations neither affected process stability nor required modifications to the underlying co-extrusion concept. As a result, both virgin and recycled continuous carbon fibre tows were successfully processed into continuous fibre reinforced thermoplastic filaments using the same manufacturing route, demonstrating the robustness and transferability of the developed process.
Representative cross-sections of the manufactured filaments are shown in Figure 6. Both filament systems exhibited continuous fibre bundles embedded within the thermoplastic matrix, confirming successful impregnation and providing the basis for the subsequent microstructural and mechanical characterization.

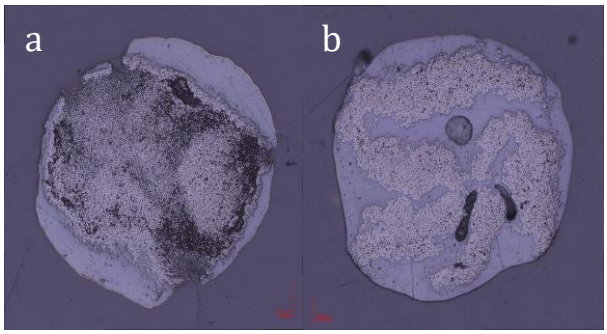

Figure 6: Cross-sectional optical micrographs of continuous fibre reinforced PPS filaments manufactured from (a) virgin and (b) recycled 12K carbon fibre tows. Both filament systems exhibit continuous fibre bundles embedded within the thermoplastic matrix. The recycled fibre filament shows locally increased variations in bundle morphology and matrix distribution resulting from the previous industrial processing history of the reinforcement.

3.2 Filament Microstructure

Representative polished cross-sections of the manufactured continuous fibre reinforced PPS filaments were analysed by optical microscopy to evaluate fibre distribution and impregnation quality.
Both filament systems exhibited continuous fibre bundles fully embedded within the thermoplastic matrix, confirming successful impregnation during the co-extrusion process [6,7]. The virgin fibre filaments displayed a comparatively homogeneous fibre distribution across the cross-section. In contrast, the recycled fibre filaments exhibited slightly larger local variations in bundle morphology and matrix distribution, which are attributed to the previous industrial processing history of the recovered carbon fibres.
Despite these local differences, no pronounced impregnation defects, extensive void formation or discontinuities of the continuous fibre reinforcement were observed. The matrix provided continuous encapsulation of the fibre bundles, indicating a sufficiently high impregnation quality for subsequent additive manufacturing.
Overall, the microstructural analysis demonstrates that the developed co-extrusion process is capable of producing structurally sound continuous fibre reinforced filaments from both virgin and recycled carbon fibre feedstocks. While the recycled material exhibits greater local variability, its overall microstructural quality is comparable to that of the virgin reference material and is suitable for the subsequent mechanical characterization and printing experiments.

3.3 Mechanical Performance

The mechanical performance of the developed continuous fibre reinforced PPS filaments was evaluated by tensile testing using specimens manufactured from both virgin and recycled continuous carbon fibre feedstocks. The corresponding results are presented in Figure 7.

Both filament systems exhibited high load-bearing capacities, confirming the successful manufacture of mechanically robust continuous fibre reinforced filaments. Under the investigated processing conditions, the recycled continuous fibre filaments achieved an average failure load of approximately 1.4 kN, compared with approximately 0.93 kN for the virgin reference material, corresponding to an increase of approximately 50%. Although both material systems exhibited a certain scatter in the measured values, the recycled filament consistently demonstrated excellent mechanical performance.

The unexpectedly high load-bearing capacity of the recycled filament indicates that continuous carbon fibres recovered from industrial production waste can be processed into structurally efficient thermoplastic composite filaments without compromising their mechanical performance. Combined with the stable manufacturing behaviour and homogeneous impregnation observed in the previous sections, these findings demonstrate that recycled continuous carbon fibre feedstocks represent a technically viable and resource-efficient alternative to virgin reinforcement for extrusion based large-scale additive manufacturing [5].

The recycled T700 production waste retained an excellent load-bearing capacity comparable to, and under the investigated conditions exceeding, that of

the virgin AS7 reference. These results indicate that the previous industrial processing history does not preclude the structural use of recycled continuous carbon fibres. A direct comparison using identical fibre grades will be the subject of future work.

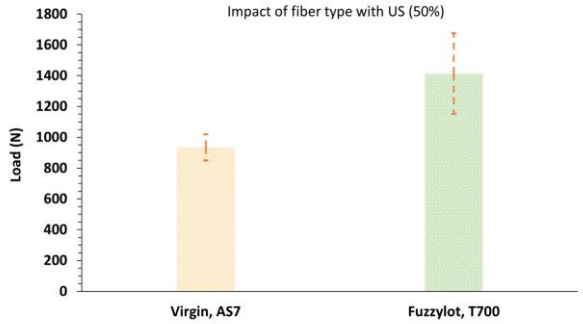

FIGURE 7: Average failure load of continuous fibre reinforced PPS filaments manufactured from virgin (AS7) and recycled (T700) 12K carbon fibre tows. The results represent the average of a minimum of five specimens per material condition tested using a tensile procedure adapted from ASTM D638 [8]. Error bars indicate the minimum and maximum measured values.

3.4 Discussion

The presented investigations demonstrate that continuous carbon fibre coming from production waste can be successfully transformed into continuous fibre reinforced thermoplastic filaments suitable for structural large-scale additive manufacturing. In contrast to conventional carbon fibre recycling approaches, which typically produce discontinuous or short fibre reinforcement with reduced structural efficiency [5], the developed manufacturing route preserves the original continuous fibre architecture and thus maintains uninterrupted load paths within the final composite.

The microstructural characterization confirmed that both virgin and recycled filament systems exhibited homogeneous impregnation without critical defects, despite the slightly greater local variability observed for the recycled reinforcement. Furthermore, the mechanical investigations demonstrated that the recycled filament system achieved a load-bearing capacity comparable to, and under the investigated conditions exceeding, that of the virgin reference material. These findings indicate that the previous industrial processing history of the recycled fibres does not preclude their use in structurally demanding additive manufacturing applications.

Overall, the combination of stable filament production, homogeneous microstructure and excellent mechanical performance demonstrates that recycled continuous carbon fibres represent a technically viable and resource-efficient feedstock for extrusion-based large-scale additive manufacturing. These results establish the material foundation for the advanced deposition strategies presented in the following section, where uninterrupted fibre crossings and support-free three-dimensional printing are investigated.

4. ADVANCED CONTINUOUS FIBRE DEPOSITION STRATEGIES

Having demonstrated the successful manufacturing and characterization of continuous fibre reinforced thermoplastic filaments from both virgin and recycled carbon fibre feedstocks, the next step is to evaluate their applicability in large-scale additive manufacturing. This section presents the development and experimental validation of advanced deposition strategies addressing two key challenges of continuous fibre printing: the realization of uninterrupted fibre crossings and the support-free deposition of three-dimensional continuous fibre reinforced structures.

4.1 Motivation

Continuous fibre reinforced thermoplastic composites are well established for the manufacture of lightweight structures using Automated Tape Placement (ATP) and Automated Fibre Placement (AFP). These technologies enable the efficient production of planar and moderately curved laminate structures with excellent mechanical performance. In contrast, comparatively little research has addressed the additive manufacturing of spatial continuous fibre reinforced structures, although such approaches offer considerable potential for realizing lightweight load-bearing components with increased geometric freedom [3,4].

Unlike conventional laminate manufacturing, extrusion-based large-scale additive manufacturing enables reinforcement paths to follow complex three-dimensional load paths rather than being restricted to stacked planar layers. This capability is particularly attractive for truss- and lattice-like structures, where continuous fibre reinforcement can efficiently carry tensile loads while maintaining a low structural weight. Consequently, support-free deposition of continuous fibre reinforced thermoplastics offers the potential to manufacture highly material-efficient lightweight structures without the need for sacrificial support material or subsequent post-processing.

Despite this potential, two major technological challenges currently limit the wider application of continuous fibre large-scale additive manufacturing. First, intersecting deposition paths typically require interruption of the continuous reinforcement or lead to localized material accumulation at crossing points. Second, successful support-free deposition requires the extruded filament to achieve sufficient mechanical stability immediately after extrusion, making the thermal behaviour of the thermoplastic matrix a critical process parameter.

The following investigations therefore focus on the development of localized toolpath strategies for

uninterrupted continuous fibre crossings and on the experimental validation of support-free three-dimensional deposition concepts for continuous fibre reinforced large-scale additive manufacturing.

4.2 Challenges of Continuous Fibre Crossings

Intersections between continuous fibre reinforcement paths represent one of the principal challenges in continuous fibre large-scale additive manufacturing. When two continuous fibre strands intersect, material is deposited twice within the same local region, resulting in increased bead height and a locally modified cross-sectional geometry. Conventional approaches typically avoid this problem by interrupting the continuous reinforcement prior to the intersection, thereby simplifying the deposition process at the expense of structural fibre continuity.

To overcome this limitation, a dedicated crossing strategy was developed that enables uninterrupted continuous fibre intersections. Instead of cutting the reinforcement, localized modifications of the deposition path are introduced to compensate for the additional deposited material while maintaining continuous fibre paths through the intersection.

A representative polished cross-section of an unoptimized fibre crossing is shown in Figure 8. The micrograph reveals pronounced local bead accumulation caused by the superposition of two deposited strands. This results in an increased bead height, localized porosity and insufficient consolidation beneath the upper strand. Such geometric irregularities impair the deposition of subsequent layers and may reduce the dimensional accuracy and structural quality of printed components [9].

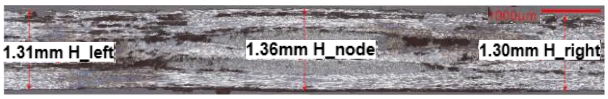

Figure 8: Cross-sectional micrograph of a baseline continuous fibre intersection without local toolpath optimization. Double deposition within the crossing region results in localized bead accumulation, increased bead height, localized porosity and insufficient consolidation beneath the upper continuous fibre strand [9].

Based on these observations, several localized notch geometries were investigated to compensate for the excess material deposited within the crossing region. The objective was to minimize local bead accumulation while preserving uninterrupted fibre continuity and ensuring stable deposition conditions. The resulting optimized crossing concept forms the basis for the deposition strategies presented in the following sections.

4.3 Continuous Fibre Crossing Strategy

Rather than interrupting the reinforcement at each intersection, a continuous crossing strategy was developed to preserve uninterrupted fibre paths throughout the printed structure. The proposed approach combines synchronized extrusion control with localized nozzle trajectory modifications, enabling intersecting continuous fibre strands while minimizing material accumulation at the node.

Based on the microstructural observations presented in section 4.2, the intersection defect was identified as a consequence of localized volumetric overload caused by the superposition of two deposited strands. To compensate for this effect, a tunnel-shaped notch is introduced into the lower strand by applying a localized vertical nozzle offset immediately before the intersection [9]. This additional volume accommodates the intersecting strand and promotes improved consolidation without requiring interruption of the continuous reinforcement. The localized notch inevitably introduces a minor geometric deviation at the crossing. However, the resulting increase in contact area between the intersecting strands improves consolidation and contributes to a stronger node connection, representing a favourable trade-off between geometric accuracy and structural integrity.

The developed crossing concept is illustrated in Figure 9. After generating the notch, the intersecting strand is deposited into the prepared cavity before the nozzle returns to the nominal deposition height. Consequently, uninterrupted continuous fibre reinforcement is maintained throughout the complete toolpath while reducing the local increase in bead height.

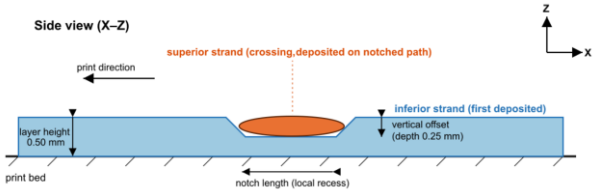

Figure 9: *Schematic illustration of the Notch Method for continuous fiber crossings.*

Several notch geometries were evaluated experimentally to identify a suitable balance between bead height reduction and consolidation quality. Particular attention was paid to preserving continuous fibre integrity while avoiding excessive local compression, which may promote fibre waviness, porosity or insufficient matrix consolidation. In contrast to conventional fibre interruption approaches, the proposed strategy relies exclusively on software-based toolpath adaptation and can therefore be implemented on existing robotic additive manufacturing systems without additional hardware modifications [9].

4.4 Thermal Behaviour During Free-Space Deposition

Following the analysis of continuous fibre crossings, the thermal conditions during deposition were

investigated to evaluate the feasibility of support-free continuous fibre printing. In contrast to conventional layer-based additive manufacturing, unsupported deposition requires the extruded filament to maintain its geometry immediately after leaving the nozzle. Since the continuous carbon fibres themselves provide only limited bending stiffness during deposition, the temporary structural stability is governed primarily by the cooling and solidification of the surrounding thermoplastic matrix. Consequently, the thermal behaviour of the deposited filament defines the process window for successful free-space manufacturing.
Infrared thermography was employed to characterize the temperature distribution of the extruded filament directly below the nozzle under representative processing conditions. A representative thermographic image is shown in Figure 10. The measurements revealed a pronounced temperature gradient, with the highest temperatures occurring immediately at the nozzle exit, followed by rapid cooling during deposition. Infrared thermography was therefore used to quantify the maximum unsupported deposition length prior to sufficient matrix solidification, which was approximately 8 mm during continuous printing and 6 mm under stationary conditions. The transition from non-self-supporting to self-supporting behaviour is gradual and therefore represents a transition zone rather than a discrete location.

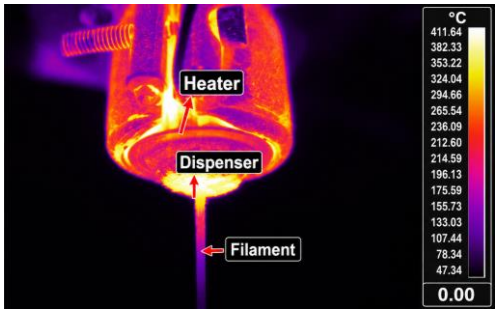

Figure 10: Infrared thermographic image of the continuous fibre deposition process showing the temperature distribution of the extruded filament directly below the nozzle under representative processing conditions.

The thermographic analysis demonstrates that the extruded filament remains highly deformable directly beneath the nozzle before progressively solidifying as its temperature decreases. Consequently, only a limited region adjacent to the nozzle lacks sufficient mechanical stability, whereas the deposited filament rapidly develops the stiffness required to maintain unsupported geometries. The identified cooling behaviour therefore defines the effective processing window for free-space deposition and determines the achievable combination of nozzle temperature, deposition speed and unsupported span length.

These observations provide the thermal foundation for the support-free deposition strategies presented in the following sections. By identifying the process window in which sufficient bonding and rapid solidification occur simultaneously, the subsequent manufacturing experiments could be performed with stable unsupported deposition while preserving continuous fibre reinforcement

4.5 Development of Support-Free Continuous Fibre Structures

Following the identification of a suitable thermal process window, the next objective was to investigate whether continuous fibre reinforced thermoplastic filaments could be deposited without sacrificial support structures. Rather than directly manufacturing complex lattice geometries, the experimental investigations followed an iterative development strategy in which the geometric complexity was progressively increased while continuously evaluating the resulting process limitations.
The initial experiments focused on the deposition of individual unsupported members in order to evaluate whether the extruded filament could maintain its geometry solely through the cooling and solidification of the thermoplastic matrix. These preliminary investigations confirmed the feasibility of unsupported deposition and provided important insight into the influence of thermal behaviour, deposition sequence and nozzle motion on the stability of the printed strand. Based on these findings, progressively more complex demonstrators comprising vertical members, inclined struts and node connections were manufactured using uninterrupted continuous fibre paths.



Figure 11. Standing triangular demonstrators manufactured without sacrificial support material. The structures served as the first benchmark for evaluating unsupported continuous fibre deposition under increasing geometric complexity.

The standing triangular demonstrators shown in Figure 11 represent the first stable support-free structures manufactured with the developed process. Their successful fabrication confirmed that continuous fibre reinforced thermoplastic filaments can be deposited without sacrificial support material while preserving uninterrupted fibre reinforcement. At the same time, the experiments revealed important process limitations. Stable manufacturing proved to be highly dependent on the selected thermal process parameters, while the continuously changing stiffness of the growing structure made the deposition sequence an essential process parameter alongside nozzle temperature and

printing speed.

Building upon these results, the developed manufacturing strategy was transferred to pyramid-shaped demonstrators introducing multiple unsupported inclined members and node intersections within a single continuous fibre path. Compared with the triangular benchmark, these geometries represent a substantially more demanding validation of the developed deposition strategy.

The successful manufacture of the pyramid structures confirmed that the identified thermal process window and optimized deposition sequence can be transferred to increasingly complex three-dimensional reinforcement architectures. Nevertheless, the larger geometries also revealed additional process limitations. Geometric deviations occurred primarily at the transitions between inclined and vertical members, where the deposited filament occasionally deflected before sufficient solidification of the thermoplastic matrix had occurred. These observations demonstrate that manufacturing stability is governed not only by thermal process control but also by nozzle accessibility, deposition sequence and the continuously increasing stiffness of the evolving structure.

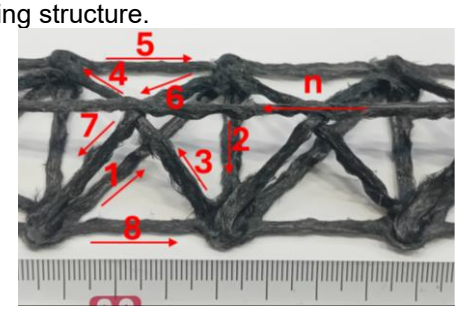

Figure 12. Evolution of the support-free deposition strategy from standing triangular demonstrators to pyramid-shaped lattice structures. The refined deposition sequence significantly improved geometric accuracy, process stability and manufacturing reproducibility.

Through iterative refinement of the deposition strategy, including optimized deposition sequencing and improved stabilization of unsupported members, the geometric accuracy and manufacturing reproducibility were significantly improved. The resulting evolution from simple unsupported members to standing triangles and finally pyramid structures is illustrated in Figure 12, demonstrating that support-free continuous fibre deposition can be systematically extended towards increasingly complex spatial reinforcement architectures. The pyramid-shaped demonstrators were selected because they combine unsupported inclined members (e.g. 3, 4, 6 and 7), vertical struts (e.g. 5, 8 and *n*), multiple node intersections (e.g. between members 3–4 and 6–7), and changes in deposition direction (e.g. member 6) within a single uninterrupted continuous fibre path, thereby representing a demanding validation geometry.

4.6 Overall Process Evaluation

The successful implementation of continuous fibre large-scale additive manufacturing relies not only on advanced deposition strategies but also on the availability of robust and reproducible feedstock materials. While the previous sections demonstrated the feasibility of uninterrupted fibre crossings and support-free three-dimensional deposition, these process developments fundamentally depend on the consistent manufacturing quality of the continuous fibre reinforced thermoplastic filaments.

Figure 13 summarizes the influence of the developed co-extrusion process on the mechanical performance of the manufactured filaments over the investigated processing conditions. In contrast to the material comparison presented in Figure 7, which evaluates representative filament systems processed under their respective optimized manufacturing conditions, Figure 13 isolates the influence of filament production speed by comparing specimens manufactured under identical process conditions (0% ultrasonic assistance and an impregnation pressure of 10 bar). The results demonstrate stable failure loads for both virgin and recycled continuous carbon fibre feedstocks, indicating that the manufacturing process provides a high degree of reproducibility despite variations in production speed. The absence of a significant reduction in mechanical performance confirms that the impregnation quality and fibre integrity are maintained throughout the investigated processing window.

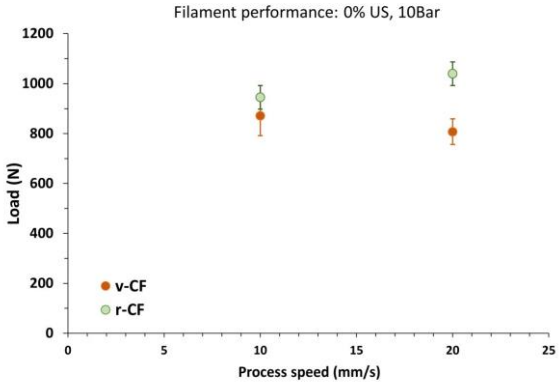

Figure 13. Influence of filament production speed on the failure load of continuous fibre reinforced thermoplastic filaments manufactured from virgin and recycled carbon fibre tows under identical processing conditions (0% ultrasonic assistance, 10 bar impregnation pressure).

These observations are particularly relevant for large-scale additive manufacturing, where continuous production of several hundred metres of reinforced filament is required for manufacturing structural components. The demonstrated process

stability therefore represents an essential prerequisite for reliable robotic deposition and validates the developed co-extrusion approach as a suitable manufacturing route for continuous fibre reinforced thermoplastic feedstocks.

The combination of stable filament manufacturing and the mechanical performance presented in section 3 establishes the material foundation for the deposition strategies introduced in the previous sections. Together, these results demonstrate that recycled continuous carbon fibres can be processed into structurally efficient feedstocks suitable for large-scale additive manufacturing without compromising manufacturing robustness.

4.7 Validation of the Continuous Fibre Crossing Strategy

Following the successful validation of the developed filament manufacturing process, the effectiveness of the tunnel-notch crossing strategy was assessed by comparing optimized intersections with the baseline deposition approach. The objective was to evaluate whether localized toolpath adaptation could improve the geometric quality of fibre crossings while maintaining uninterrupted reinforcement throughout the deposited structure.
Representative crossing geometries are presented in Figure 14. Compared with the unmodified deposition strategy, the optimized tunnel-notch approach significantly reduces local bead accumulation at the intersection. The additional cavity created within the lower strand accommodates the intersecting filament, resulting in a more uniform bead profile and improved consolidation of the crossing region. Consequently, the local increase in layer height is substantially reduced, facilitating the deposition of subsequent layers and improving the dimensional consistency of the printed structure. In the optimized configuration, the relative height increase at the intersection was reduced from 4.41 % (for the unmodified reference) to 0.73 % [9].
Beyond the geometric improvements, the developed strategy preserves continuous fibre reinforcement across the complete intersection without requiring fibre interruption or additional joining operations. This represents a key advantage over conventional continuous fibre deposition approaches, where reinforcement paths are frequently terminated prior to intersecting toolpaths to avoid local material accumulation.

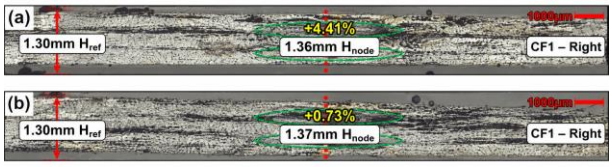

Figure 14. Microscopic comparison of continuous fibre intersections. (a) Conventional crossing showing localized material accumulation and increased bead height. (b) Optimized intersection manufactured using the Notch Method. The localized trajectory modification reduces bead accumulation while maintaining uninterrupted continuous fiber reinforcement and improving the geometric accuracy of subsequent deposition paths. (Orthogonal fiber strands are highlighted by green circles.)

The presented results demonstrate that localized software-based toolpath adaptation provides an effective solution for one of the principal geometric limitations of continuous fibre large-scale additive manufacturing. The developed strategy can be implemented without modifications to the deposition hardware and therefore offers a practical route towards manufacturing increasingly complex continuous fibre reinforced structures.

4.8 Scalable Support-Free Manufacturing of Three-Dimensional Structures

Having validated both the developed filament system and the optimized continuous fibre crossing strategy, the final stage of the experimental programme investigated the scalability of the manufacturing concept towards increasingly complex three-dimensional reinforcement structures. The objective was to assess whether the developed deposition strategies remain applicable as structural complexity and the number of unsupported members increase.

The representative demonstrators shown in Figure 15 illustrate the progression from simple unsupported geometries to increasingly sophisticated spatial reinforcement architectures manufactured along a single uninterrupted continuous fibre path. The successful fabrication of these demonstrators confirms that the developed process is not limited to isolated proof-of-concept specimens but can be extended to structures incorporating multiple inclined members, repeated node intersections, and complex three-dimensional load paths.

Stable support-free deposition was achieved only within a limited processing window. Insufficient thermal input (below 420 °C) resulted in inadequate interlayer bonding, whereas excessive thermal input (approximately 490 °C) at low printing speeds (<100 mm min^{-1}) delayed matrix solidification and promoted geometric deformation. As printing speed increased, higher nozzle temperatures were required to ensure complete filament heating. Printing speeds exceeding 1000 mm min^{-1} were only achievable at nozzle temperatures of approximately 490 °C, whereas lower speeds (<100 mm min^{-1}) could be processed below 450 °C provided that no fibre intersections were present. Conversely, excessively low nozzle temperatures resulting in poorly consolidated bead surfaces with locally exposed fibres. At fibre crossing locations,

substantially lower deposition speeds (<30 mm min^{-1}) were necessary to achieve reliable bonding while preventing fibre damage. Furthermore, unsupported node connections required an absolute positioning accuracy better than 0.1 mm to ensure reproducible node formation.

Manufacturing stability was governed by the interaction between thermal management, deposition sequence, print head accessibility, and the continuously evolving stiffness of the growing structure. During the initial deposition stages, unsupported members were susceptible to gravitational deflection before sufficient matrix solidification had occurred. As the structure developed, however, the increasing global stiffness progressively stabilised subsequent deposition, improving dimensional accuracy. The largest geometric deviations, reaching up to 2 mm, occurred at transitions between inclined and vertical members, where elevated temperatures and insufficient structural stiffness temporarily reduced positional stability.

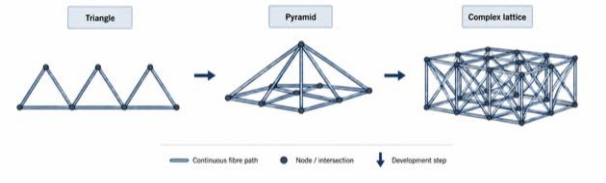

Figure 15. Progressive development of support-free continuous fibre demonstrator structures from standing triangles to pyramid geometries and complex lattice architectures.

Based on these observations, the toolpaths were iteratively refined by adapting the deposition sequence to the structural growth of the component. Previously deposited members were intentionally utilized as intermediate supports to increase the stiffness of the evolving structure, while unsupported deposition lengths were reduced to approximately 70 mm, which proved sufficient to ensure stable unsupported deposition under the investigated process conditions, resulting in significantly improved process stability and geometric accuracy.

The experimental validation demonstrates that the combination of optimized filament quality, localized fibre crossing strategies, and controlled thermal processing enables the reliable manufacture of complex continuous fibre reinforced structures without sacrificial support material. These results considerably expand the geometric design space of continuous fibre large-scale additive manufacturing and provide the technological foundation for future lightweight structural applications requiring continuous reinforcement along three-dimensional load paths.

4.9 Integrated Manufacturing Concept

The investigations presented in this chapter demonstrate that the successful realization of continuous fibre reinforced large-scale additive manufacturing requires the simultaneous optimization of both the feedstock material and the deposition process. Neither high-quality continuous fibre reinforced filaments nor advanced deposition strategies alone are sufficient to manufacture complex structural components. Instead, reliable processing is achieved through the interaction of reproducible filament manufacturing, controlled thermal management and dedicated toolpath planning.
The developed co-extrusion process enables the production of continuous fibre reinforced thermoplastic filaments from both virgin and recycled carbon fibre feedstocks with stable processing behavior and high mechanical performance. Building upon this material basis, the notch strategy overcomes one of the principal limitations of continuous fibre additive manufacturing by allowing uninterrupted fibre crossings while reducing local bead accumulation and improving geometric consistency. Furthermore, the experimental validation of support-free deposition demonstrates that increasingly complex three-dimensional reinforcement architectures can be manufactured without sacrificial support structures while maintaining continuous fibre paths throughout the complete component.
large-scale additive manufacturing technologies.

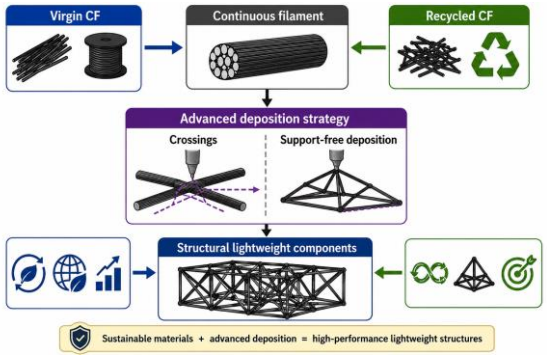

Figure 16. Integrated manufacturing concept combining continuous fibre filament production, optimized robotic deposition strategies and support-free manufacturing of three-dimensional continuous fibre reinforced structures.

The integrated manufacturing concept is summarized in Figure 16, illustrating the relationship between material development, filament production and robotic deposition. The presented process chain establishes a continuous workflow from recycled carbon fibre feedstocks to complex three-dimensional continuous fibre reinforced structures, demonstrating the feasibility of combining sustainable materials with advanced Overall, the presented approach significantly extends the manufacturing capabilities of

continuous fibre large-scale additive manufacturing by combining sustainable feedstock materials with software-based process innovations. The developed process chain provides a scalable foundation for the production of lightweight structural components with uninterrupted reinforcement and offers considerable potential for future aerospace and space applications, where both structural efficiency and resource sustainability are becoming increasingly important design requirements.

5 CONCLUSION AND OUTLOOK

This work presented an integrated approach for sustainable continuous fibre large-scale additive manufacturing by combining recycled continuous fibre reinforced filaments with novel deposition strategies for uninterrupted fibre paths and support-free three-dimensional printing. The proposed process chain demonstrates that sustainable feedstock materials can be successfully processed while simultaneously expanding the geometric capabilities of extrusion-based continuous fibre additive manufacturing.
Mechanical characterization showed that recycled continuous fibre reinforced PPS filaments exhibit a substantially higher failure load than virgin filaments, confirming their suitability as structural feedstock for large-scale additive manufacturing. In parallel, the developed continuous fibre crossing strategy successfully eliminated fibre interruptions at intersecting toolpaths without requiring additional hardware modifications. This software-based solution enables continuous reinforcement across complex deposition paths while preserving process efficiency.

To further extend the manufacturing capabilities, the thermal behaviour of the deposited filament was experimentally investigated to identify the process window required for support-free deposition. Based on these investigations, stable unsupported continuous fibre structures were successfully manufactured, progressing from simple unsupported members to increasingly complex three-dimensional lattice demonstrators. The experiments demonstrate that the rapid solidification of the thermoplastic matrix provides sufficient temporary structural stability to enable free-space deposition without sacrificial support structures. At the same time, the investigations revealed that process stability is governed by the interaction of thermal conditions, deposition sequence, nozzle accessibility and the continuously evolving stiffness of the growing structure.
Overall, the presented manufacturing concept combines sustainable material utilization, uninterrupted continuous fibre reinforcement and support-free spatial deposition within a unified process chain. The proposed approach therefore represents an important step towards the production of lightweight, resource-efficient composite structures with significantly increased design freedom for future aerospace and space applications.
Future work will focus on improving the robustness and industrial applicability of the process. In particular, optimized nozzle concepts are required to enable higher deposition speeds while maintaining adequate thermal control of the continuous fibre filament. Furthermore, strengthening fibre intersections, improving the dimensional reproducibility of unsupported structures and developing automated topology-optimized toolpath generation will further enhance process reliability and enable the efficient manufacture of increasingly complex lightweight structures. Additionally, future work should investigate improved nozzle concepts to reduce the limitations imposed by the thermal inertia of the print head and the limited heat transfer to the continuous fiber filament.

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