METHODOLOGY DEVELOPMENT FOR VOID STRUCTURE CONTROL IN CONTINUOUS FIBER-REINFORCED ADDITIVE MANUFACTURING

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ABSTRACT

Void formation in continuous fiber-reinforced additive manufacturing significantly affects structural performance and reliability, particularly in high-performance composite applications. This work presents the application of a methodology for the differentiated analysis and control of void structures based on void subtype classification, experimental parameter variation, and analytical modeling. Continuous fiber-reinforced thermoplastic filaments are manufactured under controlled conditions and analyzed using image-based techniques. Dimensionless descriptors are introduced to describe impregnation behavior. The results demonstrate improved understanding and predictability of void formation, enabling targeted process optimization and supporting future qualification strategies.

1. INTRODUCTION

Continuous fiber-reinforced additive manufacturing (CF-AM) enables the production of lightweight composite structures with high design flexibility and functional integration. Despite its potential, process-induced defects, particularly voids, remain a major limitation for structural applications. [1,2,3]

Void structures in CF-AM differ significantly depending on process conditions and material systems. Conventional evaluation methods based on total void volume provide limited insight into defect formation mechanisms. This restricts the ability to derive process–structure relationships and to enable targeted process optimization. [4]

This work addresses these limitations by applying a methodology that allows a differentiated analysis of void structures based on subtype classification and process-oriented modeling. [5,6]

1.1 Motivation

The increasing demand for lightweight, high-performance composite structures in aerospace and related industries has intensified the interest in continuous fiber-reinforced additive manufacturing (CF-AM). This technology enables the fabrication of complex geometries with integrated functionalities, offering significant advantages over conventional manufacturing processes. However, its broader industrial adoption remains limited by insufficient process reliability and the occurrence of process-induced defects. [7]

Among these defects, voids within the fiber–matrix system represent a critical challenge, as they significantly influence mechanical properties, fatigue behavior, and long-term structural stability. In particular, the presence and distribution of voids are highly dependent on process conditions, yet conventional evaluation approaches typically rely on global void volume

fractions. Such aggregated metrics provide only limited insight into the underlying formation mechanisms and do not allow for a differentiated understanding of defect structures. [8,9]

A more detailed, process-oriented analysis of void formation is therefore required to enable targeted process optimisation. In particular, distinguishing between different void types and their respective sensitivities to manufacturing parameters is essential for developing robust and transferable process knowledge. [8]

1.2 Objective

The objective of this work is the application and validation of a methodology for the differentiated analysis and control of void structures in continuous fiber-reinforced thermoplastic filaments. The methodology is based on a systematic classification of void subtypes, combined with experimental investigations and analytical modelling.

A key focus is placed on establishing quantitative relationships between process parameters and the resulting void structures. By systematically varying relevant process conditions and analysing their effects on specific void subtypes, the methodology enables a detailed understanding of defect formation mechanisms.

Furthermore, the work aims to develop physically based descriptors that capture the governing impregnation and wetting phenomena. These descriptors are used to formulate predictive models for void formation, which are subsequently validated against experimental data.

Overall, the goal is to demonstrate that the methodology provides a transferable and process-oriented framework for analysing and controlling void structures, thereby contributing to improved process understanding and supporting future efforts in process qualification and optimisation.

3. RESEARCH TESTS & EXPERIMENTS

3.1 Experimental Setup

The experimental investigations were conducted using a dedicated co-extrusion system for the production of continuous fiber-reinforced thermoplastic filaments. The setup is specifically designed to enable controlled impregnation of fiber bundles and to allow systematic variation of key process parameters affecting void formation. [10]

Within the process, dry continuous fibers are guided through a heated impregnation zone, where the thermoplastic matrix is introduced and distributed within the fiber bundle. Subsequent consolidation and shaping stages ensure geometric stability of the filament. The system is equipped with multiple control interfaces, allowing independent adjustment of relevant process variables. The setup is displayed in figure 1. [11]

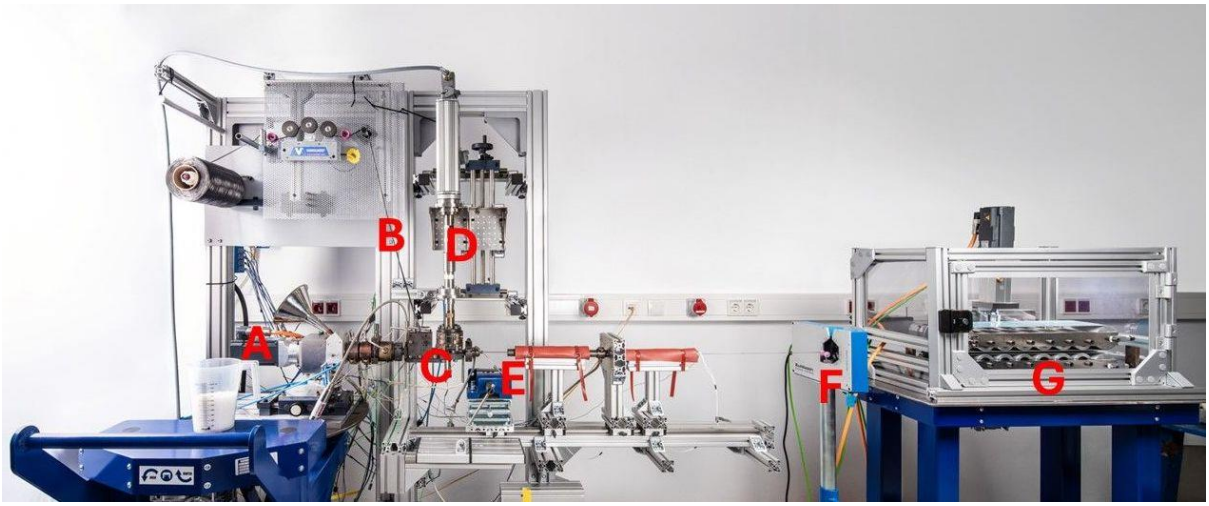

Figure 1: Filament production line: A: Extruder, B: Dry fiber guidance, C: Ultrasound transducer, D: Ultrasound impregnation unit, E: Temperature and nozzles for the filament[12]

The experimental programme focuses on the systematic variation of parameters known to influence impregnation quality and void formation. These include fiber transport velocity, consolidation pressure, and temperature distribution along the impregnation and consolidation zones. In addition, ultrasonic excitation is applied in selected experiments to enhance matrix infiltration and reduce void formation.

By combining these parameters in defined experimental series, a broad range of reproducible process conditions is generated. This enables the production of filament samples with distinct and controlled void structures, forming the basis for subsequent analysis and modelling.

3.2 Characterization Methods

The produced filament samples are analysed using a combination of image-based, mechanical, and material characterization techniques to enable a comprehensive assessment of void structures.

High-resolution microscopy is employed to capture cross-sectional images of the filaments, allowing detailed observation of void morphology and distribution. These images are processed using quantitative image analysis methods to determine void size, shape, and spatial location within the fiber–matrix system. A key aspect of the methodology is the classification of voids into distinct subtypes, enabling a differentiated evaluation of defect structures. Figure 2 displays a cross-sectional picture of the filaments. [6,13]

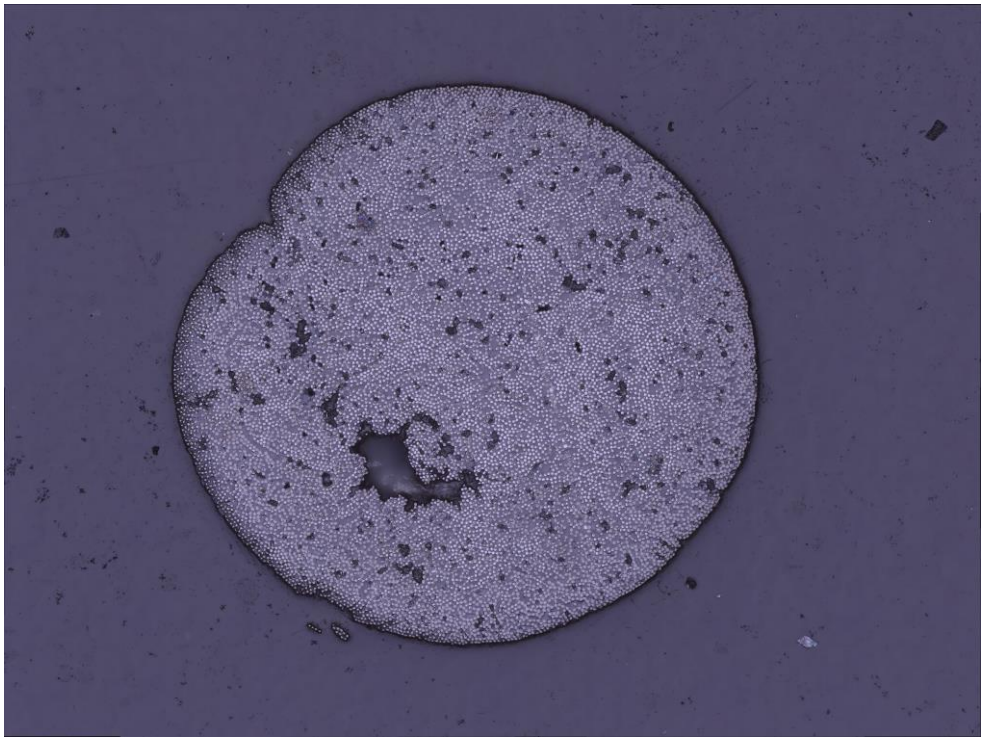

Figure 2: cross-section picture continuous fiber reinforced filament

In addition to geometric characterization, mechanical testing is performed to assess the influence of void structures on material behaviour. The results provide insight into the relationship between void distribution and structural performance.

The experimental data are further used to establish correlations between process parameters and void characteristics. Statistical analysis and regression-based approaches are applied to identify dominant parameter influences and to quantify sensitivities for different void subtypes.

This combined experimental and analytical approach provides a comprehensive dataset for the subsequent development and validation of process-oriented models describing void formation mechanisms.

4. RESULTS

The results presented in this section are structured to reflect the methodological approach developed in this work, combining experimental observations with model-based analysis. The evaluation follows a stepwise procedure, beginning with the detailed characterization of void structures and their classification into distinct subtypes, followed by the identification of process-dependent sensitivities, and concluding with the development and validation of predictive models.

The experimental campaign provides a comprehensive dataset linking controlled variations in process parameters to resulting void morphologies. This dataset forms the basis for both qualitative and quantitative analyses. Particular emphasis is placed on the transition from

descriptive characterization to analytical interpretation, enabling a deeper understanding of the underlying physical mechanisms governing void formation.

By integrating image-based void analysis with statistical and analytical modelling approaches, the methodology allows the extraction of generalized relationships between process conditions and defect structures. This enables the identification of dominant mechanisms and supports the formulation of transferable process descriptors.

The following sections present the results in detail. Section 4.1 focuses on the analysis of void subtypes and their dependence on process parameters, while Section 4.2 addresses the derivation of analytical models and their validation against experimental data.

4.1 Void Subtype Analysis

The experimental investigations reveal that void formation in continuous fiber-reinforced thermoplastic filaments cannot be adequately described by global void volume fractions alone. This is evident from the lack of a clear correlation between increasing total void volume content and the bending modulus. However, when considering void subtypes, a distinct trend becomes apparent (Figure 3). Instead, a differentiated analysis based on void subtypes provides a significantly improved understanding of defect formation mechanisms.

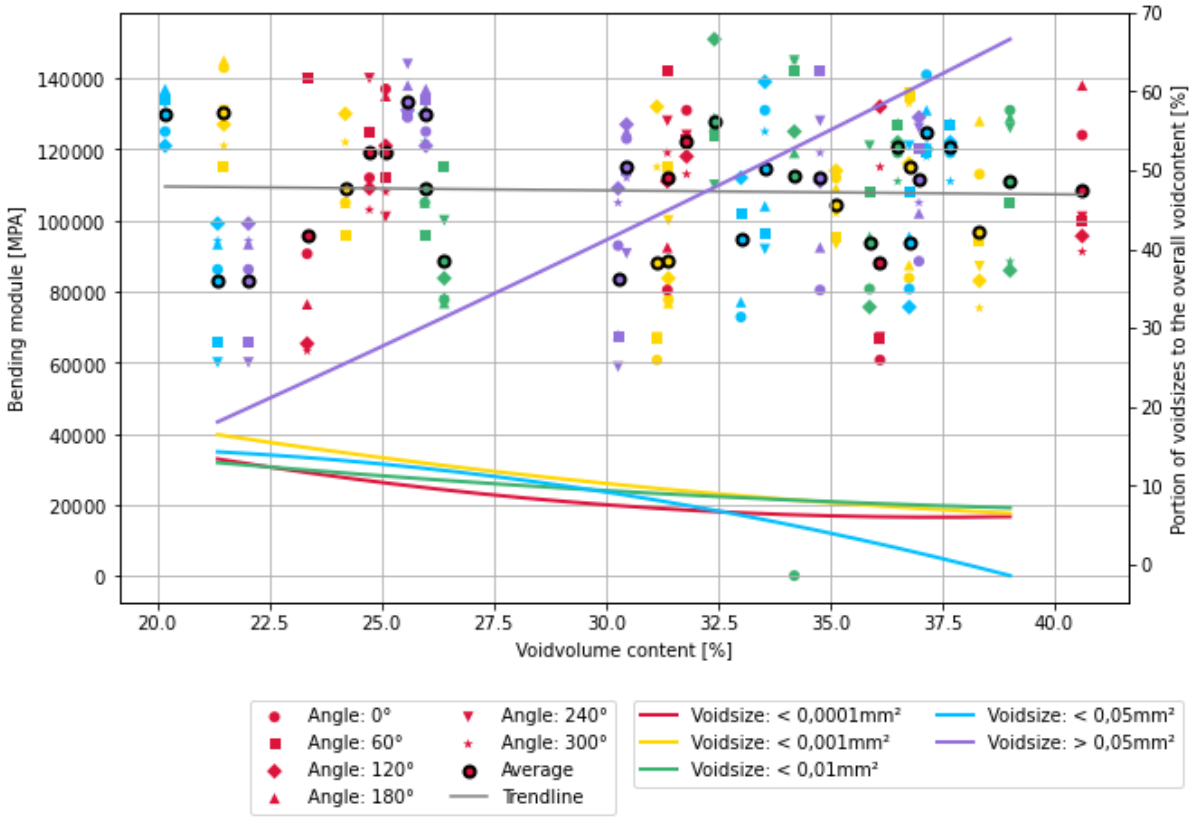

Figure 3: 1: Bending moduli in six directions with trend over the progression of the total void volume fraction (scatter plot). Data points belonging to the same specimen are color-coded for each Void volume content. 2: Proportion of different void size classes relative to the total void volume fraction (line plot). [12]

The image-based evaluation shows that the total void volume is predominantly governed by a limited number of comparatively large voids, while smaller voids occur with higher frequency but contribute less to the overall void content. This distinction is critical, as different void subtypes exhibit fundamentally different formation mechanisms and sensitivities to processing conditions.

The classification into void subtypes enables a detailed analysis of their spatial distribution within the fiber–matrix system. Certain void types are predominantly located within fiber bundles, indicating insufficient impregnation, whereas others are associated with interfacial regions or consolidation effects. This spatial differentiation provides insight into the governing physical mechanisms, such as capillary-driven infiltration, local pressure distribution, and flow constraints within the fiber architecture.

Systematic variation of process parameters (impregnation pressure, fiber velocity, material combination and ultrasound amplitude (Table 1)) demonstrates that individual void subtypes respond differently to changes in processing conditions.

Table 1: Material and Parameters used for the produced filaments

Material		Parameters		
Fiber	Polymer	US Intensity [%]	Speed [mm/s]	Impregnation Pressure [bar]
T700 SC50C	PPS	0	5	10
Toray M40B	PLA	20	10	20
AS7 Hexcel		50	20	30

For example, an increase in consolidation pressure leads to a reduction of larger voids associated with incomplete impregnation, while smaller void structures remain comparatively unaffected. Similarly, variations in fiber transport velocity influence the available impregnation time and thus directly affect the formation probability of specific void types.

These findings confirm that a subtype-based evaluation is essential for identifying dominant defect mechanisms and for enabling targeted process optimisation.

4.2 Model Development and Validation

Based on the experimental observations, analytical relationships describing the impregnation process are derived. The modelling approach is grounded in the physical mechanisms governing matrix infiltration into fiber bundles, taking into account viscous flow behaviour, capillary effects, and time-dependent impregnation dynamics.

Two dimensionless (Ca^* and dr/dR) descriptors are introduced to characterise the process conditions. The modified capillary number Ca^* represents the balance between viscous forces and capillary-driven infiltration, while the normalized impregnation depth dr/dR describes the extent of matrix penetration into the fiber bundle relative to the available processing time. These parameters provide a physically meaningful framework for comparing different process conditions and material systems.

The two approaches are the capillary number [6] and a measure of the possible impregnation depth due to permeability and fiber velocity [12].

$$Ca^* = \frac{\mu\, v}{\gamma\, cos\varphi}$$

and

$$\frac{dr}{dR} = \sqrt{2}\frac{K\, K_v}{\mu(1-\varphi_F)}\frac{dP}{dR} * \frac{dX}{v_F}$$

(μ: viscosity, v: velocity, γ: surface tension, $cos\varphi$: fiber-polymer contact angle, K: permeability, K_v: ration between orthogonal and lateral permeability, φ_F: fiber volume content, P: pressure, R: Radius, r: distance in radial direction, X: length of impregnation cell)

Regression-based models using linear, quadratic, logarithmic and exponential terms are developed to establish quantitative relationships between process parameters and the occurrence of specific void subtypes. The models demonstrate that distinct void types can be correlated with characteristic ranges of the dimensionless descriptors, indicating that their formation is governed by identifiable physical regimes.

The predictive capability of the methodology is evaluated by comparing model-based predictions with experimentally observed void structures across multiple material systems. The results show a high level of agreement between predicted and measured void distributions, particularly for dominant void subtypes contributing to the overall defect structure. The comparison is displayed in figure 4.

Furthermore, the methodology proves to be transferable across different material combinations and processing conditions. Despite variations in material properties such as viscosity and surface tension, the dimensionless representation allows consistent interpretation of the underlying mechanisms.

Overall, the results demonstrate that the combination of subtype-based analysis and physically grounded modelling provides a robust framework for understanding and predicting void formation. This enables a transition from purely empirical observations to a knowledge-based approach for process evaluation and optimisation.

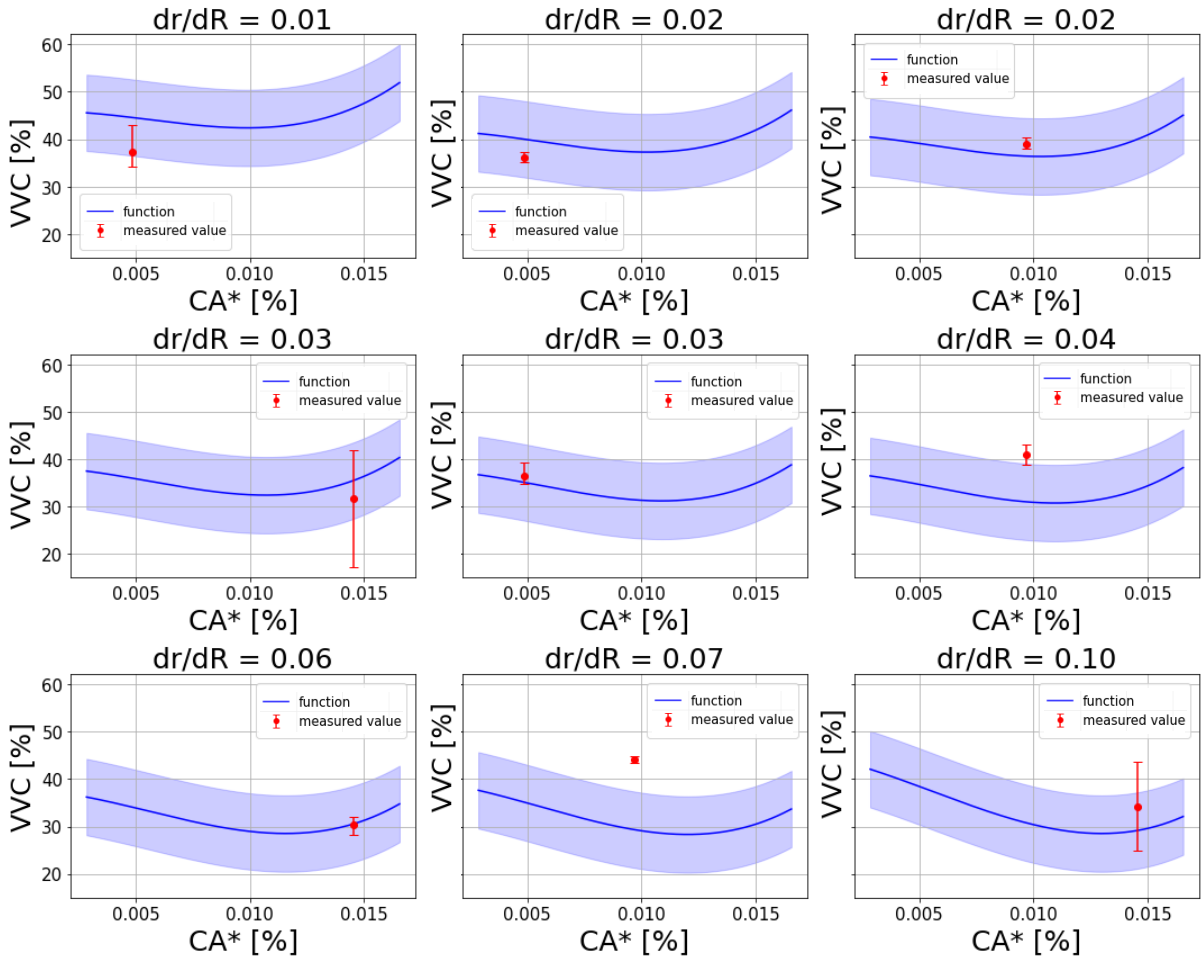

Figure 4: Comparison between regression approach and measurement [12]

5. CONCLUSIONS

This work demonstrates the successful application of a methodology for the differentiated analysis and control of void structures in continuous fiber-reinforced thermoplastic filaments. By combining systematic void subtype classification, controlled experimental investigations, and physics-based modelling, a comprehensive framework for analysing void formation has been established.

The results highlight that void formation cannot be sufficiently described using global metrics such as total void volume alone. Instead, the differentiation into distinct void subtypes provides significantly enhanced insight into defect formation mechanisms and their dependence on process parameters. This enables a more targeted evaluation of process conditions and supports the identification of dominant influencing factors.

Furthermore, the introduction of dimensionless descriptors allows the representation of complex impregnation phenomena in a physically meaningful and transferable manner. The good agreement between model predictions and experimental observations confirms the validity of the analytical approach and demonstrates its applicability across different material systems.

5.1 Key Contributions

The main contributions of this work lie in the development and application of a methodology that enables a differentiated and process-oriented analysis of void structures in continuous fiber-reinforced thermoplastic filaments. By introducing a systematic classification of void subtypes, it is possible to move beyond conventional global void metrics and to analyse defect structures with significantly higher resolution. This allows the identification of subtype-specific sensitivities to process parameters and provides deeper insight into the underlying formation mechanisms.

Furthermore, the work establishes quantitative relationships between process conditions and resulting void structures through the combination of experimental investigations and regression-based modelling. In addition, the introduction of dimensionless descriptors, such as the modified capillary number and normalized impregnation depth, provides a physically grounded framework for describing impregnation behaviour across different material systems and processing conditions.

The validation of the developed models against experimental data demonstrates the predictive capability of the methodology and confirms its transferability. Overall, the presented approach represents a significant step towards a knowledge-based understanding of void formation and enables more targeted process evaluation and optimisation in continuous fiber-reinforced additive manufacturing.

5.2 Outlook

The presented methodology provides a robust foundation for further developments in process optimisation and qualification of continuous fiber-reinforced additive manufacturing processes.

Future work will focus on extending the methodology to printed structures and multi-axis manufacturing processes, where additional effects such as deposition-induced defects and inter-layer bonding become relevant. Furthermore, the integration of the methodology into process monitoring and simulation environments offers the potential for real-time defect prediction and control.

In the context of high-performance applications, the approach may contribute to improved reliability assessment and support the development of qualification strategies for additively manufactured composite components. The transfer of the methodology to different material systems and process configurations represents a key step towards its broader applicability in advanced composite manufacturing.

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