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ANALYSIS OF VOID-SIZE AND VOID-DISTRIBUTION IN CONTINOUSLY FIBER REINFORCED FILAMENTS FOR ADDITIVE MANUFACTURING

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ABSTRACT

Voids are well understood in traditional composite manufacturing processes. However, the evolving technology of fiber-reinforced additive manufacturing, with its unique constraints, requires adapting this knowledge to the specific materials and processes involved.

This paper evaluates the presence of different void types in continuously fiber-reinforced filaments used for composite additive manufacturing. It presents a study in which the void volume content of a filament, as well as the distribution of void sizes, is correlated with mechanical properties. Due to significant data scattering that complicates a clear evaluation, the study also investigates void mitigation strategies, focusing on the most detrimental void types in the printed parts—since the final printed component's quality is more relevant than the raw filament alone.

A distinct influence of certain void sizes is identified, indicating that these voids should be prioritized for reduction over others.

1 INTRODUCTION

Fiber-reinforced additive manufacturing, whether using short or continuous fibers, improves the properties of the base polymer depending on the type and volumetric content of the fibers. While short fibers often provide sufficient stiffness for a structure, continuous fibers are necessary to increase strength in specific sections [1].

There are different manufacturing technologies to produce such filaments. One versatile method is co-extrusion. For this technology, the German Aerospace Center (DLR), Institute of Lightweight Systems (SY), developed a patented process that uses ultrasound to improve filament quality.

Aeronautical applications require volumetric void contents below 2%. Since this applies to the final part, it is necessary to evaluate not only the void content of the filament after production but also to consider how the printing process affects voids within the filament [2].

Voids in the filaments occur at various scales. As filament diameters are about 1.1 mm (800 tex, 12K, 50% fiber volume content), the usual void classification cannot be directly applied. However, the typical classification into micro-, meso-, and macro-voids can be adapted for this purpose.

High-performance polymers such as Polyetherimide (PEI), Polypropylensulfide (PPS), and Polyetheretherketone (PEEK) are used because the material must meet high-performance requirements to justify its cost. These polymers tend to have relatively high viscosity, which challenges the co-extrusion process.

2 MATERIALS AND METHODS

Materials and production process:

The produced, printed, and evaluated filaments consist of carbon fibers from the AS7 fiber by Hexcel, which is a 12K fiber with 800 tex and no sizing. The polymer matrix is a commercially available PPS . The impregnation temperature is 330 °C, resulting in a measured dynamic viscosity of 155 Pa·s without applied shear forces.

The filament is manufactured on a co-extrusion line with a miniaturized extruder capable of processing about 2 kg of polymer per hour. The fiber insertion tool is designed to allow dry fibers to enter while sealing the polymer-fiber contact area to up to 60 bar. An ultrasound impregnation cell is used to improve impregnation by reducing the polymer viscosity.

A hydraulically decoupled two-nozzle concept shapes the filament into a round semi-finished product according to the specimen requirements. Tempered tubes at the interface and after the last nozzle enable a gentle cooling ramp. The filament is then spooled and used on the printing end effector, where it is heated in a thermally decoupled nozzle. The nozzle diameter is only slightly larger than the filament diameter to reduce fiber buckling in the molten polymer, which can cause nozzle clogging.

Producing fiber-reinforced thermoplastic products is challenging in terms of quality assurance because the matrix material has higher viscosity and exhibits both elastic and viscous behavior [3]. Multiple production technologies exist, but most are not easily transferable between material systems. The classical fiber impregnation approach using e.g. thermoset matrix systems results in different void types—macro, meso, and micro voids—classified according to their location relative to the fiber tow [4]. Since this process uses only one tow, the classification must be adapted.

Methods:

The analysis of the filament after production and after printing single strands consists of multiple evaluation steps. First, the filaments are cut into specimens for 3-point bending tests. The specimens are marked with rotation angles to repeat measurements in six directions. Additionally, specimens are sputtered, cut, and polished to enable optical analysis of the voids present.

The bending tests are conducted according to ISO 178/141425. The bending results of each specimen are compared based on the loading direction (in 60° increments). The optical analysis results are benchmarked against overall void content measured by thermogravimetric analysis.

The optical analysis uses an automated algorithm to distinguish voids from fibers and polymer based on grey-scale thresholds. However, voids vary widely in symmetry, location, size, and shape. While the classical classification into micro-, meso-, and macro-voids could be applied to the cross-sectional Figure 1, the distinction is not always clear in literature. Therefore, voids are categorized in this paper by size into following classes: '< 0.0001 mm²', '< 0.001 mm²', '< 0.01 mm²', '< 0.05 mm²', and '> 0.05 mm²'.

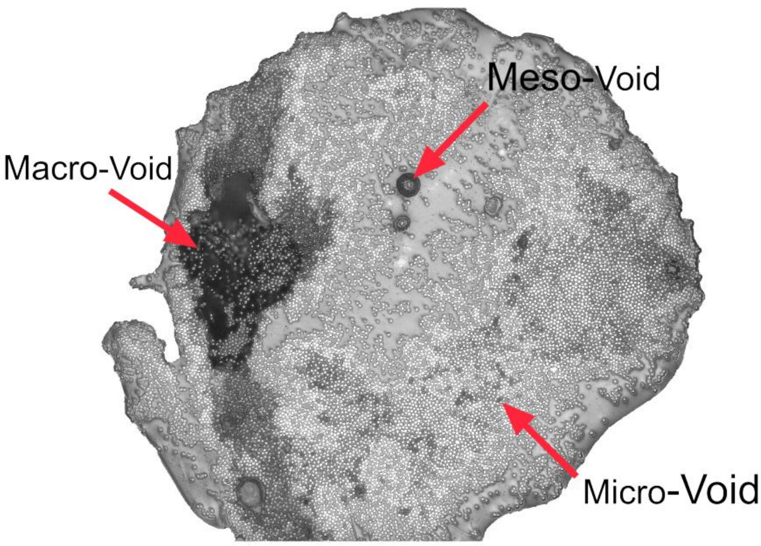


Figure 1 Modification of classical void classification

A main evaluation experiment is using three-point bending test. The experiment is designed using the norm DIN EN ISO 14125 [5]. However, since the filament is round, the pins were modified to position the filament according to the desired rotational positioning. The bending is set force driven (1N) newton to not provoke destructive testing as each specimen is needed for 6 measurements.

For the shear test, the filament is clamped into a rotational test device in which an oscillating, rotational movement is applied. Using the amplitude and the frequency, the shear modulus can be calculated [6].

3 EXPERIMENTS

To assign mechanical behavior to the voids, the described methodology was applied. Numerous filaments made from the same material combination—PPS and AS-7 fiber—were produced. However, manufacturing parameters such as production speed, impregnation pressure, and ultrasound impregnation amplitude were varied. The impregnation line speed ranged between 10 and 50 mm/s, while the impregnation pressure was set between 20 and 30 bar.

Figure 2 shows the calculated bending modulus of single filaments plotted against the global void volume content determined from cross-sectional images. For each filament, results from different angles of attack (0°, 60°, 120°, 180°, 240°, 300°) are indicated. It is important to compare opposite angles to reveal asymmetries in mechanical performance and the overall scattering of results. Average values are also presented. However, across more than 30 specimens with void volume content between 20–40%, no clear trend emerges from the data. Manufacturing pressure and speed were varied in order to produce different void volume contents.

The graph also includes information on the content of individual void size classes relative to overall void content. It appears that when a certain total void content is present, large voids dominate the void population, whereas smaller voids show less correlation with overall void content.

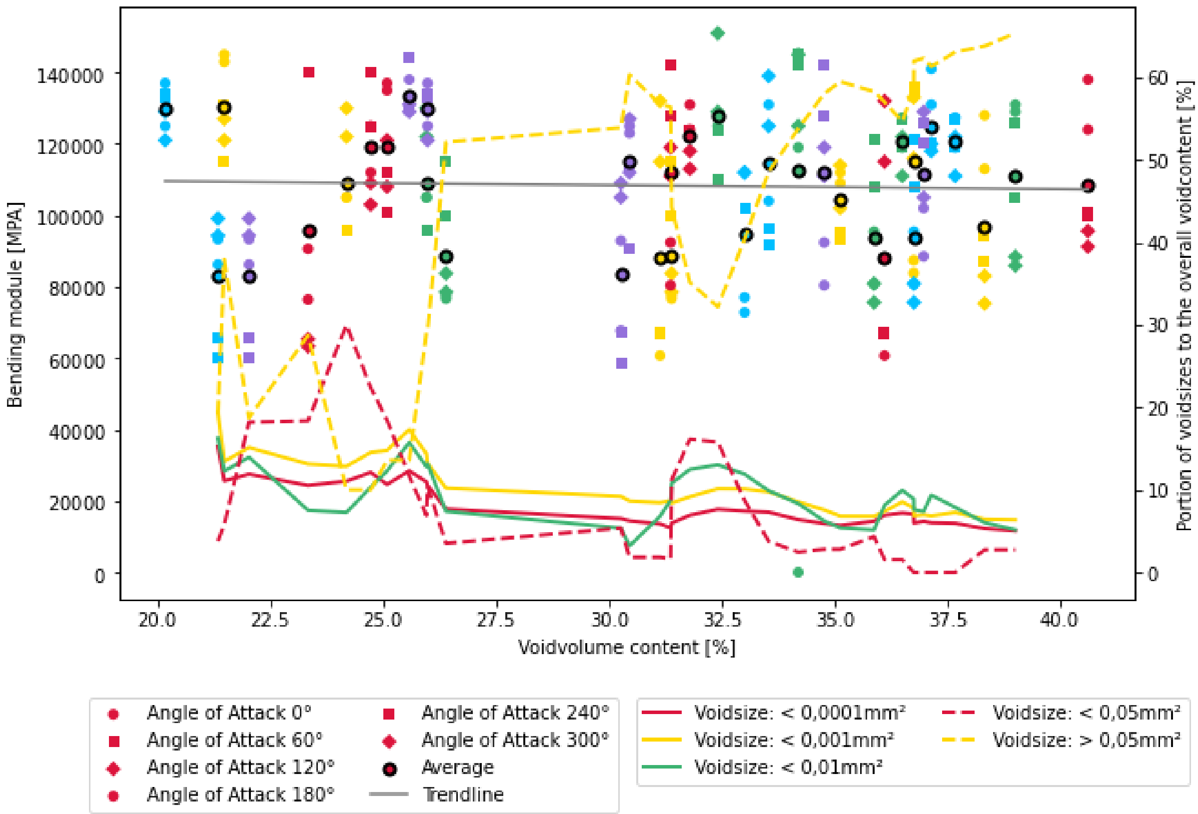


Figure 2 Bending to void volume content

Since bending tests did not reveal a significant correlation between voids and mechanical properties, the shear modulus was also tested and calculated (Figure 3). Again, results do not show a clear influence of increasing void content; interestingly, the expected loss in mechanical performance is not observed.

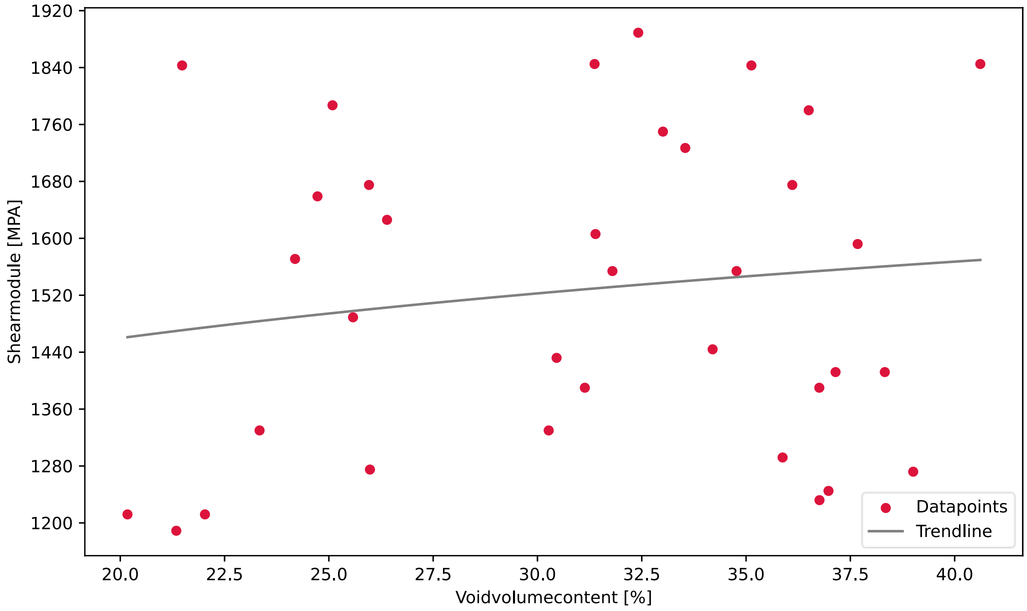


Figure 3 Shear modulus compared to the void volume content

Because void volume content does not correlate well with filament mechanical properties, a new approach is needed to analyze the influence of voids and their types. It is evident that data scattering is significant and that mechanical properties depend on additional factors which may mask the void effect. Major influencing parameters include fiber distribution and filament geometry as well as overall quality of impregnation. While the filament shape can be controlled relatively well with the machine setup, fiber distribution is less controllable and causes asymmetrical voids expected to have greater impact on bending and shear modulus than overall void content.

Since void restrictions mainly apply to the final additively manufactured part, not the filament material itself, the mitigation of voids during filament printing was evaluated.

Therefore, each filament batch was used in a classical FDM (Fused Deposition Moulding) where only a single filament was deposited, eliminating side effects like polymer oozing or acceleration/deceleration of the print head positioning system (Figure 4).

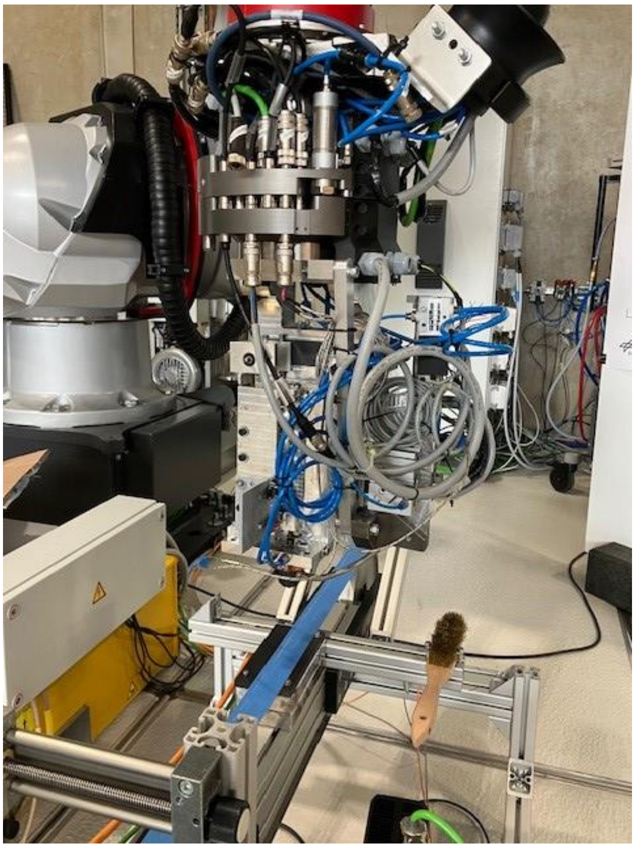


Figure 4 Filament printing

Subsequently, 3-point bending tests on printed filaments were conducted (Figure 5). Data shows a tendency of the printing influencing the bending modulus and void content, but no clear impact of printing speed is discernible.

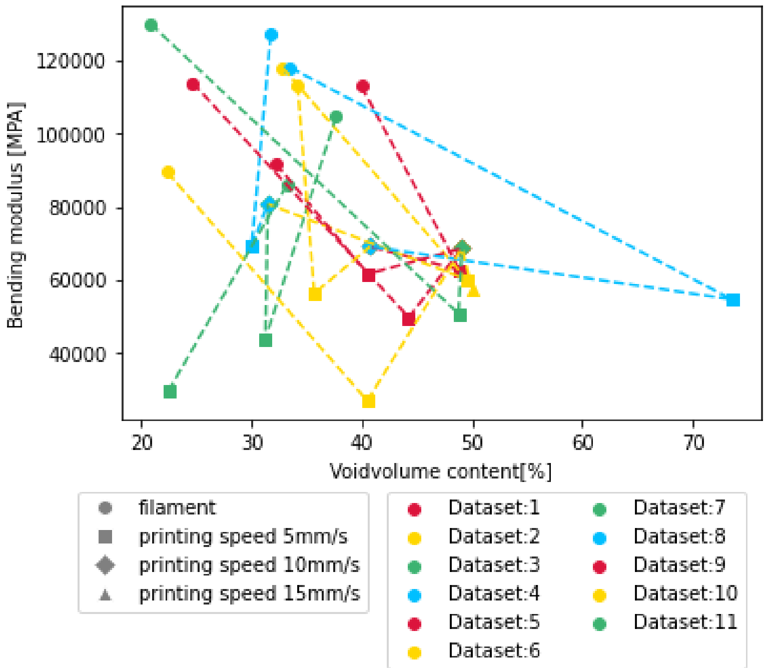


Figure 5 Bending of printed filaments

Optical evaluation of filaments before and after printing reveals a significant increase in voids due to printing.

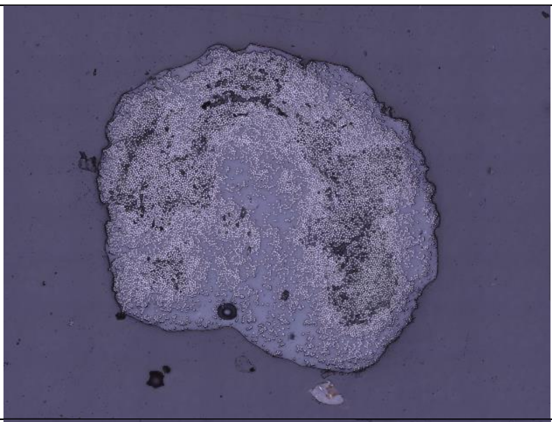
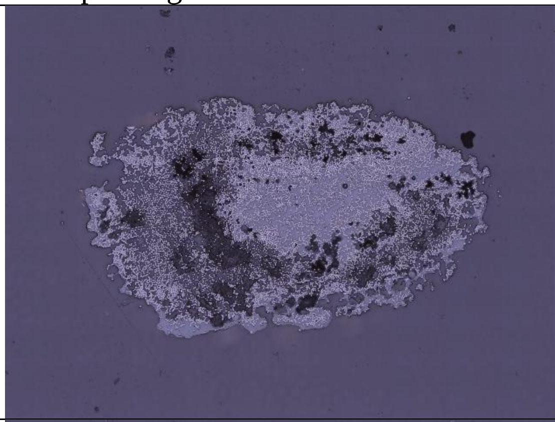
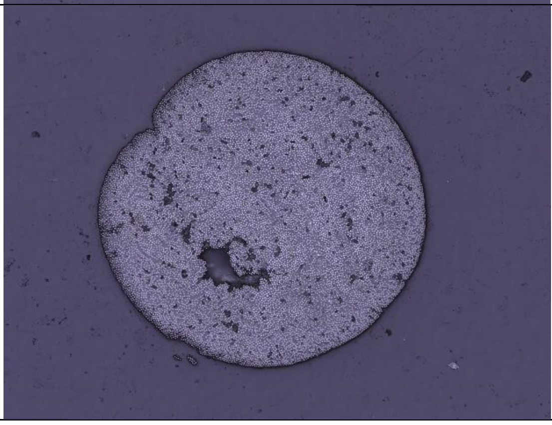
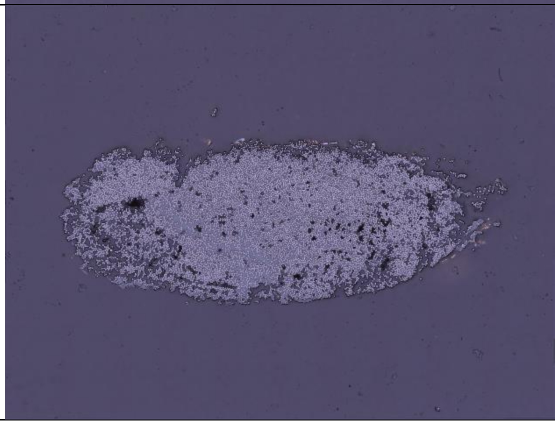
	Filament	After printing
1		
2		

Table 1 Filament comparison to printed version

Table 1 presents four microscopic images showing large voids in filament 1 and only medium-sized voids in filament 2. Notably, printed filament 1 shows a significant increase in voids, while filament 2 only has a slight increase. Figure 6 quantifies this effect across evaluated specimens.

Voids smaller than 0.05 mm^2 do not tend to accumulate or grow significantly, whereas voids larger than '> 0.05 mm^2' tend to increase, initiating cracks and raising overall void content during the process of printing the filament. The printing speed shows only minor influence, likely within data scattering.

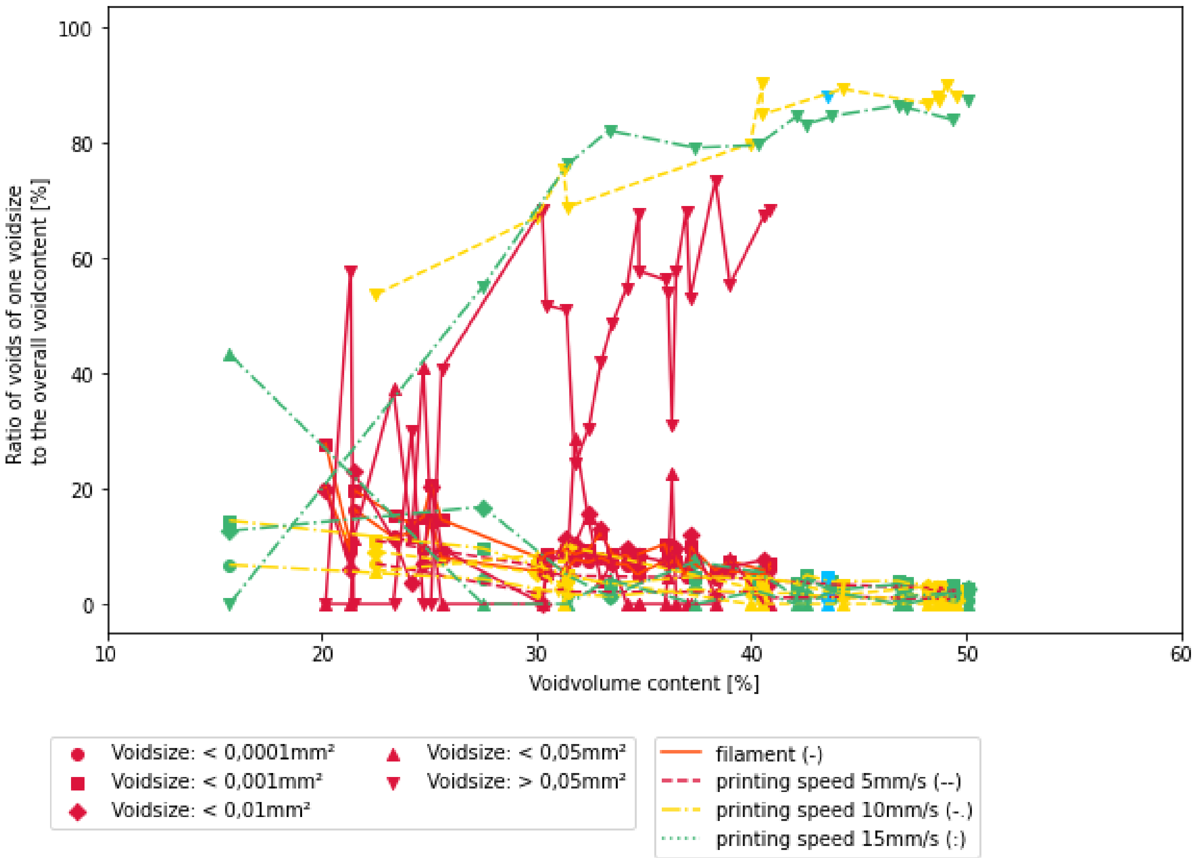


Figure 6 Void content comparison filament to printed specimen

4 CONCLUSION AND OUTLOOK

This study analyzing filaments produced by the co-extrusion process shows that the influence of voids on mechanical properties—such as bending modulus and shear modulus—is largely within the scattering caused by inhomogeneous fiber distribution as well as impregnation quality and imperfect filament geometry.

Nevertheless, certain types of voids have a notably harmful impact, especially when their mitigation is considered. While small individual voids appear largely unaffected by the printing process, larger voids significantly affect the printed parts by increasing the overall void content, which can lead to part rejection due to insufficient quality.

Given the manufacturing challenges of continuous fiber reinforced filaments, based on the utilized production process using ultrasound induced impregnation it seems to be not feasible to eliminate all voids immediately. However, this study identifies which void types should be prioritized for reduction.

Future work should investigate additional mechanical properties influenced by voids in the final parts. Moreover, improvements in fiber distribution are necessary to reduce the variability in material performance. Both theoretical considerations and engineering experience suggest that increased void content generally leads to reduced mechanical performance. By isolating other influencing factors, it may become possible to quantitatively assess the effects of void size, geometry, location, and type on mechanical behavior.

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