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Mechanical properties of additive manufactured components with combined short and continuous fiber reinforcement

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Abstract
Additive manufacturing of fiber-reinforced plastics offers high potential for lightweight applications through combining short fiber-reinforced polymers with continuous fibers. While individual fiber types have been investigated, limited research exists on optimizing double fiber-reinforced components. This study analyses continuous glass fiber reinforcement in tensile strength of additively manufactured components made of short fiber-reinforced polyamide 6 (Onyx). Samples with varying fiber content, layer positioning, and reinforcement strategies are manufactured and tested. Results show that increasing fiber content significant enhances tensile strength, while the exact position of the fiber layers within thin specimens has only a minor influence. Continuous fiber reinforcement also achieves comparable properties with reduced infill.

additive manufacturing, fused filament fabrication (FFF), short fiber-reinforced polymers, continuous fiber, tensile tests

1. Introduction

Additive manufacturing of fiber-reinforced plastics offers great potential for industrial and lightweight applications, combining design freedom with adjustable mechanical properties. Short fiber-reinforced polymers combined with continuous fibers increase strength and stiffness [1, 2]. Few studies examine systematic optimization of double fiber-reinforced components [3]. This work investigates the influence of continuous glass fiber (CGF) reinforcement on mechanical properties of tensile specimens, varying fiber content, layer arrangement, and reinforcement design.

2. Experimental setup

Tensile specimens were produced from the short carbon fiber-reinforced filament Onyx and selectively reinforded with CGF, both supplied by Markforged Inc. (Watertown, USA). Onyx consists of polyamide with a short carbon fiber (CF) fraction of $11\,\% \leq \phi_{CF} \leq 15\,\%$ [4]. It offers increased stiffness, good toughness, high chemical and thermal resistance. CGFs were fed from a spool and introduced during printing in specific layers or as outlines.The component design was carried out using NX CAD software from the company Siemens AG (München, Germany) while process preparation and fiber placement were performed using Eiger slicer software. The investigated parameters included the continuous fiber content, the number and position of the reinforced layers, the infill density, and the reinforcement layout. The samples were produced using an Onyx Pro FFF system (2nd generation, Markforged Inc., Watertown, USA). This desktop 3D printer has a build volume of 320 mm × 132 mm × 154 mm and allows the processing of short fiber-reinforced filaments and the integration of continuous fibers [4]. The Onyx material was processed at θ_{Onyx} = 275 °C and the CGF at θ_{CGF} = 230 °C. Depending on the specimen variant, either ρ_{infill} = 100 % solid infill or ρ_{infill} = 37 % triangular infill was used, while both Onyx and glass fibers (GF) were generally deposited in alternating ±45° orientation, except for the Onyx100_LinesGF configuration.

3. Experimental Procedure and Analysis

3.1. Tensile test specimens

Standardized tensile specimens with different reinforcement strategies were produced and mechanically tested to evaluate the influence of CGF reinforcement. Tensile test specimens were made of short fiber-reinforced polyamide and, depending on the variant, additionally reinforced with CGFs. Unreinforced specimens served as references. To investigate continuous fiber influence, fiber content, positioning, and reinforcement design were varied, resulting in GF fractions of $11.4\,\% \leq \phi_{GF} \leq 24.8\,\%$ (Table 1). In addition to fully reinforced layers, variants were also considered in which the CGFs were applied exclusively as concentric outlines. Samples with reduced polymer infill were also produced in order to evaluate the influence of the material content in conjunction with continuous fiber reinforcement (CFR). All samples were produced lying flat, with the continuous fibers being laid alternately in a ±45 °orientation in all cases.

3.2. Tensile Testing

The mechanical characterization of the samples was carried out using quasi-static tensile tests. These were performed at a test speed of s = 2 mm/min, a preload of p = 3 N, and a clamping length of l = 200 mm. An extensometer with a measuring range of r = 25 mm was used to precisely record the strain. Five samples were tested for each test variant, resulting in a total of 35 tensile samples being examined. Depending on the variant, the CGF content of the reinforced samples ranged from $11.4\,\% \leq \phi_{GF} \leq 24.8\,\%$ (Table 1). The elastic modulus E_t, maximum strain ε_{max}, and tensile stress σ_m were determined from the stress-strain curves (Figure 1).

Sample designation	Onyx-Infill	Endless GF	GF layers	Order of GF layers	Elastic modul (E_t)	Max. strain (ε_{max})	Tensile stress (σ_m)	GF content
Onyx100_0GF	100 %	no	-	-	566.37 MPa ± 61.49	61.77 % ± 12.03	28.08 MPa ± 1.30	0 %
Onyx100_4GF	100 %	yes	4	full surface	1580.32 MPa ± 41.35	3.77 % ± 0.16	46.01 MPa ± 3.51	16.2 %
Onyx100_6GF	100 %	yes	6	full surface	2138.28 MPa ± 186.17	3.76 % ± 0.15	61.50 MPa ± 3.41	24.4 %
Onyx100_6GF3	100 %	yes	6	full surface (each 3. layer)	1956.98 MPa ± 94.25	3.69 % ± 0.09	58.16 MPa ± 2.48	24.8 %
Onyx100_LinesGF	100 %	yes	several	outlines	3273.92 MPa ± 72.47	3.50 % ± 0.16	107.29 MPa ± 3.97	11.4 %
Onyx37_0GF	37 %	no	-	-	464.33 MPa ± 23.08	45.93 % ± 8.01	16.73 MPa ± 0.33	0 %
Onyx37_4GF	37 %	yes	4	full surface	2072.82 MPa ± 57.06	4.10 % ± 0.26	55.37 MPa ± 2.70	16.2 %

Table 1 Overview of the tensile samples examined and results of tensile testing

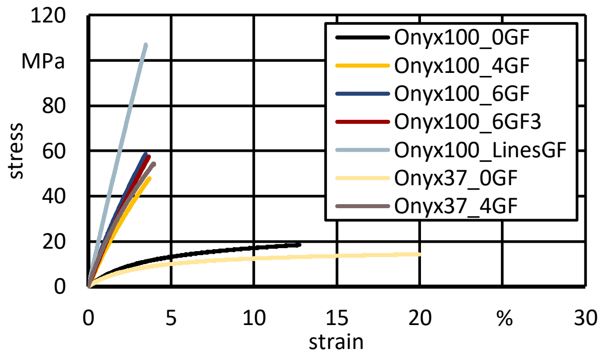

Figure 1. Stress-strain diagram

The diagram shows that increasing CGF content leads to higher tensile strength, while variations in fiber positioning at a constant number of reinforced layers have only a minor influence. Specimens reinforced with CGF outlines achieve the highest tensile strength (σ_m = 107.29 MPa). Although reduced polymer infill generally decreases strength, CFR compensates for this effect, as specimens with 37 % infill and four GF layers exceed the strength of fully filled specimens. These trends are consistent with previous studies reporting increased strength and stiffness with higher continuous fiber content [6]. Based on the elastic modulus, pure Onyx specimens can be classified as semi-rigid plastics, whereas continuous fiber-reinforced specimens exhibit rigid material behavior, which is reflected by a steeper initial slope and more brittle fracture in the stress–strain curves. In addition to the stress–strain curves, the fracture behavior of the tensile specimens was analyzed to identify dominant damage mechanisms. Figure 2 shows representative fracture features observed after tensile testing:

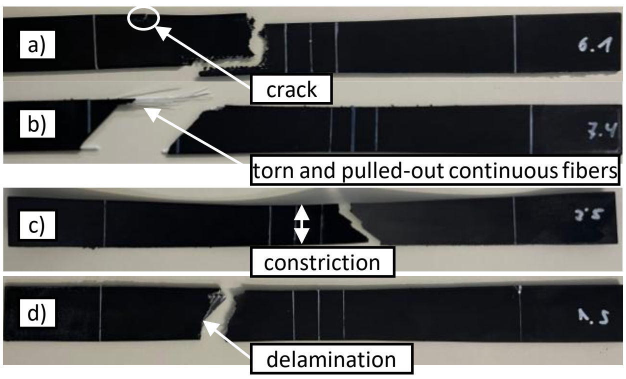

Figure 2. Breaking behavior of the tensile specimens (a: Onyx100_6GF, b: Onyx100_LinesGF, c: Onyx37_0GF, d: Onyx37_4GF)

In specimens reinforced with CGFs, a low and narrowly distributed strain at failure in the range of 3.4 % ≤ ε_{max} ≤ 4.1 % was observed, indicating brittle, fiber-dominated failure. Pronounced crack initiation at the specimen edges is visible in Figure 2a, indicating local stress concentrations. These cracks form first and propagate, leading to failure after multiple cracks. In specimens reinforced only by continuous fiber outlines, such as Onyx100_LinesGF, failure occurs abruptly without prior crack growth (Figure 2b). Pulled-out and exposed CGFs are observed, while the surrounding polymer matrix fails along the Onyx infill pattern, indicating limited bonding, insufficient limited stress transfer, and local interfacial debonding between fiber outlines and infill regions. Specimens without CFR exhibit a different failure mode, with pronounced necking prior to fracture (Figure 2c), reflecting ductile matrix behavior. Local delamination between CGF layers and the surrounding matrix is observed in Figure 2d. These interfacial separations indicate insufficient bonding under tensile loading, reduce the efficiency of load transfer between fiber and matrix, and contribute to reduced elongation and more brittle fracture behavior of continuous fiber-reinforced specimens.

4. Conclusion

This study investigated the influence of combined short fibers and CFR on additively manufactured tensile specimens. CGF reinforcement increases tensile strength and stiffness with higher fiber content further improving mechanical properties, while layers positioning has only minor influence. Fracture mechanisms correlate with the stress-strain response, indicating increased stiffness and strength at the expense of ductility, while enabling high strength at reduced infill.

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