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Investigating the Influence of Fiber Orientation on Tensile and Flexural Properties of Additively Manufactured Continuous Glass Fiber-Reinforced Nylon Composites

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Abstract. Additive Manufacturing (AM) has revolutionized the manufacturing industry by enabling the fabrication of complex and customized components with unprecedented design freedom. In recent years, there has been a significant focus on extending the capabilities of AM to produce fiber reinforced composites, which offer exceptional mechanical properties and enhanced performance characteristics. This article evaluates the tensile and flexural (three-point bending) properties of additively manufactured continuous glass fiber-reinforced nylon composites (CGFRNCs). Composites are designed using constant fiber volume fraction (V_f) and variable fiber orientations ($\boldsymbol{\theta}$) by US-based Markforged's 'Mark Two' 3D printer. V_f is 27% for all composite coupons and $\boldsymbol{\theta}$ is varied by 0°, 45°, 90°, and 135° (or -45°). Experimental results show the maximum tensile strength of 225.78 MPa for 0° and maximum flexural strength of 82.84 MPa also for 0°. Damage analysis has been carried out in X-ray Micro Computed Tomography.

Keywords. Additive Manufacturing, Composites, Fiber orientation.

1. Introduction

Additive Manufacturing (AM), also known as 3D printing, is a layer-by-layer technique of joining successive layers of materials on top of each other to create objects from digital 3D CAD model data, opposed to traditional subtractive manufacturing [1,2]. AM has recently attracted significant interest over traditional manufacturing techniques, owing to its several benefits such as the ability to fabricate complex shapes, design flexibility, mass customization, low manufacturing costs, automated processes, reduced waste, improved dimensional accuracy, and fast prototyping [3]. Nowadays composites are popularly being manufactured by additive manufacturing. Hence, this work focuses on effective design for additive manufacturing (DFAM), fiber parameterization, and optimization to get effective mechanical properties. Ibrahim M Alarfi et. al. [4] reported the tensile and flexural strength for short glass and carbon fiber reinforced nylon composites. Andrew N Dickson et. al. [5] reported the tensile and flexural strength for continuous glass, carbon, and kevlar fiber reinforced nylon composites for 0° fiber orientation only. Our study claims the variation of fiber orientation using a fixed fiber volume fraction for glass fiber reinforced nylon composites.

2. Materials and methods

For making composites by Additive Manufacturing, Nylon-6 filament of 1.75 mm diameter was used as a matrix material and continuous glass fiber bundle of 0.3 mm diameter was used as a reinforcement material. Both materials were purchased from Markforged, USA. Markforged produces its own proprietary materials for its 3D printers. 'Mark Two', a thermoplastic composite 3D printer by Markforged was used to manufacture these composites. This printer has two nozzles fitted in a single extruder where one nozzle is for matrix material, and another is for reinforcing fiber. Before usage, Nylon-6 was kept in a Pelican-1430 modified dry box that was sealed against the infiltration of moisture. The fiber bundle contains 1000 individual fiber tows and appeared to be each of 10 µm diameter based on Scanning Electron Microscopy (SEM) images. These tows are infused and held together by a sizing agent i.e., also Nylon-6. Printing starts with the deposition of Nylon-6 by nozzle-1 followed by deposition of glass fiber by nozzle-2. Fig. 1 shows the nylon-6 and glass fiber spools followed by 'Mark Two' 3D printer, schematic of CFF process, and geometries of tensile and flexural specimens.

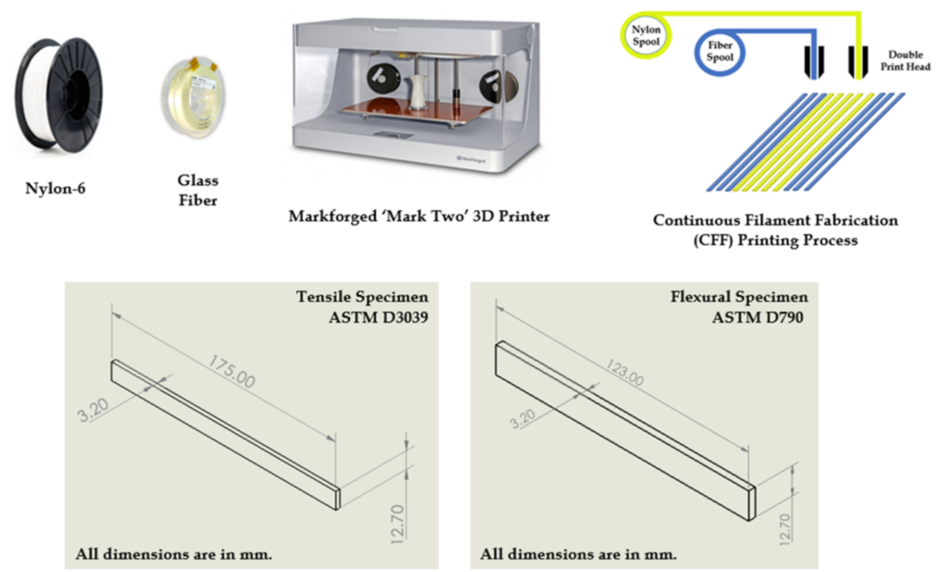

Figure 1. Materials, methods, and specimens' geometry

3. Results and discussion

3.1. Experimental results

Tensile and flexural tests were performed on Zwick Roell 250 UTM machine. For tensile test, the specimen is securely clamped between upper and lower jaws, encompassing 50 mm on each side, resulting in a gauge length of 75 mm. Flexural specimens was having span length of 51.2 mm that is 16 times of specimen thickness. And the load was applied to the centre of the specimen. Constant rate of elongation (CRE) theory was followed to perform both tensile and flexural test by applying constant strain rate of 2 mm/min and 2.2 mm/min respectively.

Tensile strength ($\boldsymbol{\sigma_t}$) is a measure of elongation force applied per unit cross-sectional area and is calculated as

$$\boldsymbol{\sigma_t = F/A}$$

Flexural strength can be calculated as,

$$\boldsymbol{\sigma_f = \frac{3FL}{2bh^2}}$$

And flexural strain will be calculated as,

$$\in_{\mathbf{f}} = \frac{\mathbf{6h\delta}}{\mathbf{L^2}}$$

Where, $\boldsymbol{\sigma_f}$ - Flexural stress, $\in_{\mathbf{f}}$ - flexural Strain, **F** – force applied, **b** – specimen width, **h** - specimen thickness

$\boldsymbol{\delta}$ – deflection, L – span length, A – cross-sectional area

3.1.1. Effect of fiber orientation on tensile strength

TNG1 specimen, with a fiber orientation of 0°, exhibited the highest tensile strength of 225.78 MPa. This outcome can be attributed to the fact that the fibers in this configuration were aligned parallel to the applied load, allowing for efficient load transfer along the fiber axis. On the other hand, the TNG2 specimen with a 90° fiber orientation demonstrated significantly lower tensile strength of 20.06 MPa. In this case, the fibers were oriented perpendicular to the loading direction, leading to reduced load-bearing capacity and increased vulnerability to fiber delamination and interfacial failure. Similarly, the TNG3 specimen with a 45° fiber orientation displayed a tensile strength of 24.76 MPa, indicating a compromised load-bearing capability due to the inclined alignment of fibers. Finally, the TNG4 specimen, which incorporated a combination of 0°, 45°, 90°, and -45° fiber orientations, exhibited an intermediate tensile strength of 181.67 MPa.

Table 1. Tensile strength data of specimens

Sample ID	Fiber orientation	Tensile Strength (MPa)	Tensile Strain (%)	Tensile Modulus (GPa)
TNG1	0°/0°/0°/0°	225.78	5.01	3.95
TNG2	90°/90°/90°/90°	20.06	15.63	0.497
TNG3	45°/45°/45°/45°	24.76	12.25	0.505
TNG4	0°/45°/90°/-45°	181.67	5.28	4.48

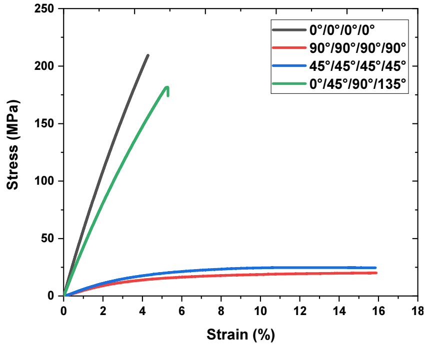

Figure 2. Stress strain curve for tensile strength

3.1.2. Effect of fiber orientation on flexural strength

FNG1 specimen, with a fiber orientation of 0°/0°/0°/0°, exhibited the highest flexural strength of 82.84 MPa. This result can be attributed to the fact that the fibers were aligned parallel to the applied load, allowing for efficient load transfer and resistance to bending stresses. In contrast, the FNG2 specimen, with a 90°/90°/90°/90° fiber orientation, displayed a significantly lower flexural strength of 24.93 MPa. In this configuration, the fibers were oriented perpendicular to the loading direction, leading to reduced load-bearing capacity and increased vulnerability to interlaminar shear and delamination. Similarly, the FNG3 specimen with a 45°/45°/45°/45° fiber orientation exhibited a flexural strength of 31.24 MPa, indicating a compromised load-bearing capability due to the inclined alignment of fibers. The FNG4 specimen, incorporating a combination of 0°, 45°, 90°, and -45° fiber orientations, demonstrated an intermediate flexural strength of 69.83 MPa.

Table 2. Flexural strength data of specimens

Sample ID	Fiber orientation	Flexural Strength (MPa)	Flexural Strain (%)	Flexural Modulus (GPa)
FNG1	0°/0°/0°/0°	82.84	4.87	2.78
FNG2	90°/90°/90°/90°	24.93	8.77	0.685
FNG3	45°/45°/45°/45°	31.24	8.48	0.707
FNG4	0°/45°/90°/-45°	69.83	8.63	2.2

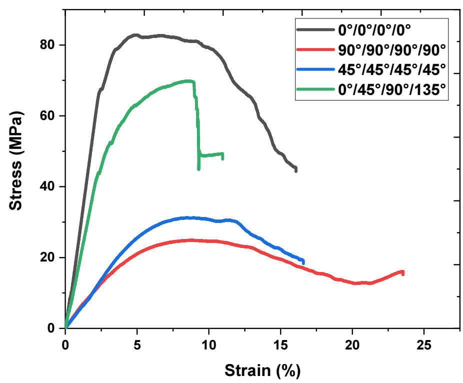

Figure 3. Stress strain curve for flexural strength

3.2. Micro CT analysis

In addition to evaluating mechanical properties, micro-computed tomography (micro-CT) was employed to investigate the internal damage mechanisms in the composite specimens subjected to varying fiber orientations. The micro-CT analysis allowed for a detailed examination of the fiber composite structure, providing insights into specific failure modes. For 0°/0°/0°/0° and 0°/45°/90°/-45° orientations, the analysis revealed the presence of fiber splitting, which refers to the separation of individual fibers along their length. This phenomenon was observed due to the high tensile stresses experienced by the fibers aligned parallel to the loading direction. In contrast, for the 90°/90°/90°/90° orientation, micro-CT imaging highlighted the occurrence of fiber delamination, where the layers of fibers separated from each other, resulting in a loss of interfacial strength. Finally, the 45°/45°/45°/45° orientation exhibited significant fiber breakage, where fibers fractured under the combined effect of tensile and shear stresses. These micro-CT findings can be utilized to optimize the design and manufacturing processes, ultimately leading to the development of composites with improved structural integrity and enhanced resistance to failure.

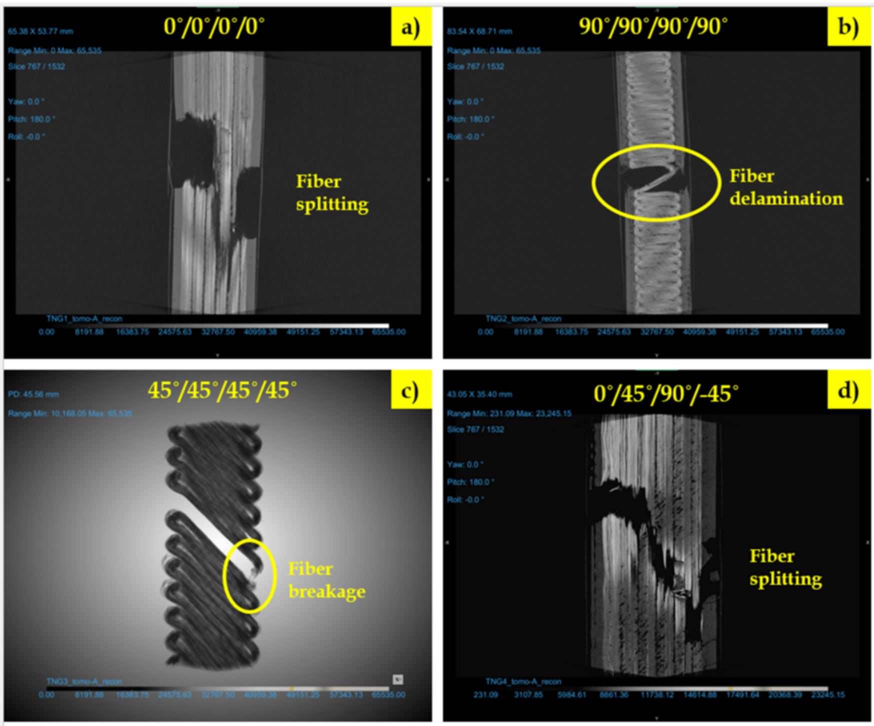

Figure 4. Micro CT images of fractured specimens

Conclusion

In conclusion, our study investigated the effects of varying fiber orientation on the tensile and flexural strength of composite materials, while keeping the fiber volume fraction constant. By examining four different orientations (0°, 45°, and 90°), as well as a combination of 0°/45°/90°/-45°, we aimed to understand the influence of fiber alignment on the mechanical properties of the composites. Our findings indicate that the 0° fiber orientation consistently yielded the highest tensile and flexural strengths among all tested configurations. This result suggests that aligning the fibers parallel to the loading direction enhances the load-bearing capacity of the composite material. These findings have significant implications for the design and manufacturing of composite structures, as they highlight the importance of carefully considering fiber orientation to achieve optimal mechanical performance. Future research can explore additional factors, such as the effect of different fiber volume fractions and matrix materials, to further enhance our understanding of composite behavior and improve the performance of composite materials in various applications.

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