

You are what you breathe: observing airborne carbon fiber particulates during FFF printing of PA6-CF filament

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Abstract: Carbon fiber reinforced filaments are increasingly popular in Additive Manufacturing (AM) due to their enhanced mechanical properties compared to traditional materials like PETG, ABS, and Nylon. However, these materials present challenges, including proper drying requirements and potential fiber transfer to the skin during handling. In this study, microscopic examination of fingertips after handling PA6-CF parts revealed significant fiber transfer, raising concerns about airborne fiber dispersal during printing. This research aims to observe the dispersion of fibers from PA6-CF filament using a Bambu Lab X1C desktop Fused Filament Fabrication (FFF) system. A custom apparatus with filter was developed to capture dispersed fibers during printing experiments. The used filters were then observed for fiber content to draw conclusions. Safety precautions are recommended along with a proposed alternative slicing method to minimize fiber transfer from final parts. This study contributes to a safer working environment for 3D printing enthusiasts and professionals by addressing potential health risks associated with airborne fiber dispersion.

Keywords: Fused Filament Fabrication (FFF), Carbon Fiber Reinforcement, Air Filtration, Airborne Fibers

1. Introduction

Material Extrusion (ME) is one of the most common types of Additive Manufacturing technologies used today, where material is deposited layer-by-layer through a nozzle in a controlled manner (toolpath). Material can vary, being a slurry or gel but often molten plastic is used for manufacturing parts, in the form of filament or pellets [1]. This is specifically known as Fused Filament Fabrication (FFF) [2]. Carbon fiber (CF) reinforced filaments are increasingly popular in FFF due to their enhanced mechanical properties compared to traditional materials like PETG, ABS, and Nylon [2]. These materials are made by adding short, chopped fibers into a base polymer [3]. This is detailed in the filament's material datasheet, provided by the manufacturer, including the percentage by weight of chopped fibers. It is known that parts made via the FFF process introduce variability beyond the material type, where process parameters such as build orientation and raster angle, among others, play a role in the final strength of the part [4]. The performance of composite filaments includes an added variability, the orientation of chopped fibers in the plastic and the percentage of fiber volume in the entire volume of the print, also known as the fiber volume fraction (FVF) [5]. Strength performance is not the focus of this work, however the inconsistencies due to embedded chopped fibers should be noted. In literature, it is often assumed that the direction of fibers majorly follows the toolpath of a print, yet surface examination of final printed parts seen later in this work show some exposed surface fibers (Figure 2) [6]. These materials also present challenges, including proper drying requirements due to high moisture and potential fiber transfer to the skin during handling [5]. The motivation for this work stems from the qualitative observation of the transfer of chopped fibers from handling both raw filament and manufactured parts using Nylon 6-CF (PA6-CF) and PLA-CF. This work begins to address the gap in literature in understanding the existence of airborne chopped carbon fibers during FFF printing and the difficulty in measuring them.

2. Materials and methods

This work examines the transfer of chopped fibers to fingers tips through the handling of final printed parts (Bambu Lab PLA-CF and PA6-CF). The base polymer and chopped carbon fiber percent by weight for these filaments is summarized in Table 1, extracted directly from the manufacturer's Safety Data Sheets (SDS). From these specifications, chopped CF fibers in Bambu Lab materials range in 0.05 mm to 0.2 mm in length, with assumed diameter between 0.005 mm to 0.010 mm [7]. To explore how easily chopped fibers would dislodge from the final part, the surface of a print was rubbed with fingertips for about 30 seconds. A microscope camera was then used to visually capture any chopped fibers present on fingertips before and after handwashing.

Table 1. Base polymer and chopped carbon fiber [% by weight] of explored filaments.

Bambu Lab filament	Base polymer [% by wt]	Chopped CF [% by wt]
PLA-CF [8]	Polylactic Acid, 90-95	5-10
PA6-CF [9]	Nylon 6 and copolymer, 80-88	12-20

A custom nozzle shroud was designed to house a filter with the goal of capturing airborne chopped fibers during the printing of PA6-CF on the Bambu Lab X1C desktop FFF machine. The shroud in Figure 1(a)(b), was fabricated with PETG material for improved inter-layer bonding and heat resistance to avoid potential deformation from residual heat during printing PA6-CF (requiring 270 °C nozzle and 100 °C build plate temperatures).

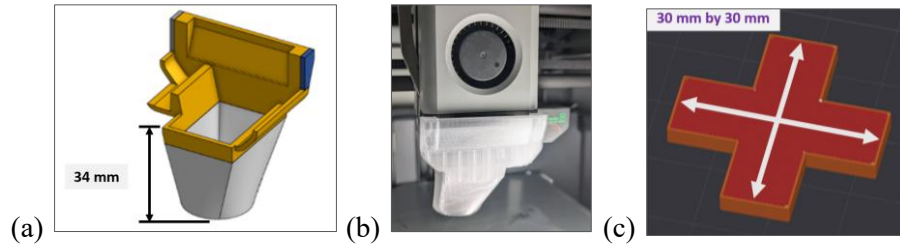


Figure 1. (a) CAD model of custom shroud, (b) shroud secured to printer tool head and (c) sliced test file geometry.

A cellulose-based filter covered in an adhesive layer was attached to the inside of the shroud and used to capture airborne chopped fibers present during extrusion, encapsulating the tool head fans, as they directly control/influence air flow around the nozzle. Due to the newly added length to the tool head, the G-code of the test file was modified with a fixed Z height of 75 mm to avoid collisions with the build plate. The rest of the G-code was preserved, including extrusion length, feed rate, fan speed (100%) and tool head speed as these factors were assumed to influence potential of existing airborne chopped fibers and their flow in the environment of the printer. A simple test geometry was used, a cross-shape with height of 3 mm and bounding box of 30 mm by 30 mm, (Figure 1(c)). A 0.4 mm nozzle, 0.2 mm layer height, and 100% infill at 45° raster angle was used for slicing/printing.

3. Results and discussion

3.1. Qualitative results from PLA-CF & PA6-CF handling

After handling final PA6-CF parts, a microscope camera was used to observe and capture transferred chopped fibers to fingertips. Due to page limitation and data security, not all images are included of finger pads. A representative analysis of a 5 mm by 5 mm fingertip surface area revealed the presence of 35 short fibers and 3 longer fibers immediately following material contact. Post-handwashing, less fibers were observed, with few remaining visibly embedded in the tougher skin of the fingertip and hidden under the fingernail. Figure 2 illustrates some of these observations, including previous PLA-CF insights. It is clear the base polymer affects how well fibers are retained.

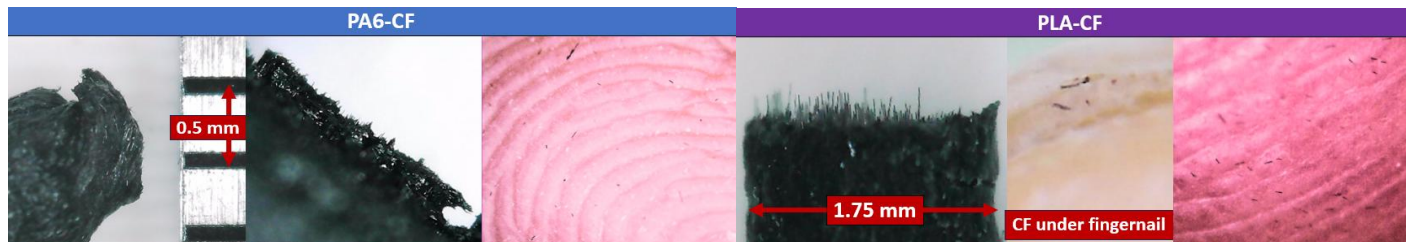


Figure 2. Exposed chopped fibers from filament strand, printed part and skin transfer of Bambu Lab PLA-CF and PA6-CF.

3.2. Observation of airborne carbon fibers during printing

Before printing, each adhesive filter panel was weighed. Initially, one test print was performed with the fiber capturing shroud. Very few fibers were visible using the microscope camera for initial qualitative results. Nine more test samples were extruded making a total of ten tests (≈ 7.2 m or 18.9 g of extruded PA6-CF), weighing the filter panels after (Table 2). Figure 3 presents captured carbon fibers and other particulates collected on filters after PA6-CF extrusion testing, with fiber dimensions approximated based on chopped carbon fiber specifications from the manufacturer. Unfortunately, the manufacturer provides a range of % by weight in chopped fibers, thus, assuming 20 % of the extruded filament is CF (3.8 g or 0.0038 kg), the change in weight of filters (0.152 g) suggests that ≈ 4 % of the extruded chopped fibers were captured as airborne particles. This measured capture can be an underestimate due to the un-enclosed nature of the shroud, done to minimize extrusion build up during printing, which would potentially allow for the escape of airborne fibers. Yet, potential sources of measurement uncertainty also include the incidental collection of dust or other particulate matter by the adhesive filters, both during the sampling period and while handling. More tests should be conducted. Another clear limitation is quantifying the exact percentage of chopped fiber in the filament, which would allow for a better analysis of fiber release.

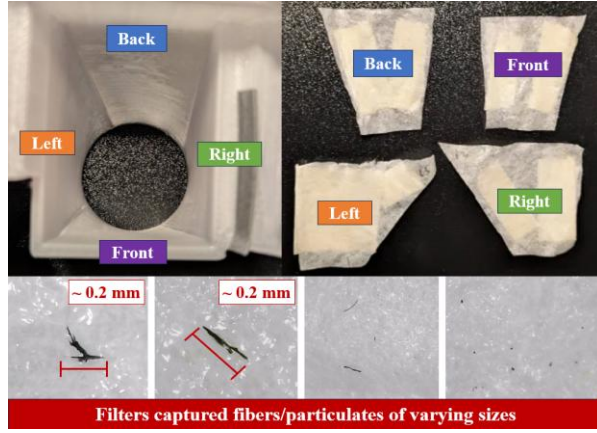


Figure 3. Labeled filter panels from fan shroud (top) with microscope images of select chopped carbon fibers and particulate matter collected during PA6-CF extrusion tests (bottom).

3.3. Recommendations for printing safely

As FFF systems are an accessible industrial process capable of being brought into homes and office/lab spaces, certain precautions should be taken. Ideal operation includes avoiding printing in the same room occupied by persons. Due to the higher temperature (both hot end and chamber) associated with printing CF materials, enclosing the system is required, and this allows for proper filtration and ventilation. Knowing printer filter locations and replacement cycles and referencing a material's safety data sheet (SDS) is necessary. Wearing gloves and safety glasses as well as hand washing after use when handling CF filament can minimize skin contact and potential fiber transfer to eyes. Post processing methods such as sealing finished CF parts with clear coat enamel paint or using alternative slicing strategies during pre-processing, as detailed in the section below, can retain surface fibers from transferring.

3.4. Slicing strategy for minimizing fiber transfer during handling

To minimize fiber transfer through skin contact during handling of a final print using CF filaments (Figure 2), an alternative slicing strategy and multi-material approach is proposed. PLA material was used to print the outer walls (2) and top and bottom layers (2 each) of the tensile sample, enclosing the PLA-CF material, which was used to print the core of the sample. Data has been collected to explore tensile strength of this method, following the ASTM D638 standard. All samples were printed at a X0 Y0 Z0 orientation with two walls, two top and bottom layers at 0.2 mm layer height with a 0.4 mm nozzle, 100% infill and 45° raster angle. Three samples for each case study (PLA only, PLA-CF only, and multi-material) were performed with averages summarized in Table 3 and comparative tensile stress-strain curves shown in Figure 4. These tests were performed using Bambu Lab PLA and PLA-CF due to availability and multi-material compatibility at the time of these tests. Similar tests should be performed with Nylon 6 for direct comparability. Notably, the dual material samples showed greater ductility and peak load before failure (slight increase in ultimate tensile strength and strain at break) in comparison, but potential brittleness after sample necking seen through its low fracture stress. This analysis considered the trade-off between performance and safer end-use parts.

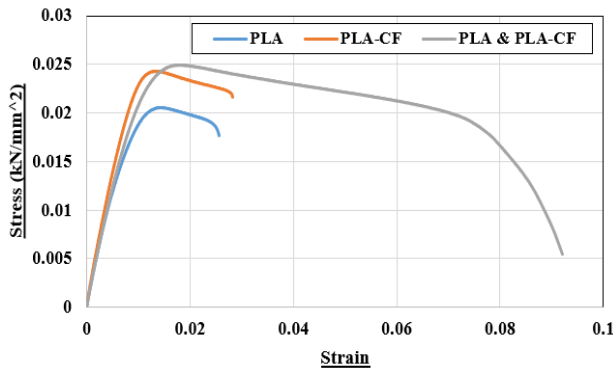


Figure 4. Comparative tensile stress-strain curves showing one from each sample type: PLA, PLA-CF, and multi-material PLA/PLA-CF (n=3 each).

Table 2. Filter observations and change in weight (g) before and after printing ten consecutive test samples.

Filter Section	Weight before printing [g]	Weight after printing [g]	Change in weight [Δg]
Front	0.130	0.151	0.021
Back	0.100	0.133	0.033
Left Side	0.118	0.200	0.082
Right Side	0.152	0.168	0.016
Total	0.500	0.652	0.152

Table 3. Comparison of select tensile stress strain curves and summary of average extracted mechanical properties.

Tensile Property	PLA	PLA-CF	PLA & PLA-CF
Young's Modulus [kN/mm ²]	2.596	2.839	2.395
Yield Stress [kN/mm ²]	0.018	0.019	0.020
Ultimate Stress [kN/mm ²]	0.024	0.023	0.025
Fracture Stress [kN/mm ²]	0.02	0.02	0.005
Strain at break	0.025	0.027	0.087

4. Conclusion

This work is successful in observing both the skin transfer of chopped fibers via material and final part handling and the presence of airborne chopped fibers during the printing process. To move towards repeatable qualitative results, the next steps should focus on improved methodologies and acquiring precise equipment for more reliable assessment of airborne fiber concentrations. This would include the design of a better fiber capturing strategy, potentially including a sensor system. To strengthen these findings, modeling of the airflow and airborne release from an FFF nozzle when printing fiber-reinforced filaments can be explored. To model the airflow in a printer, the following should be considered: nozzle convection and added fans (both hot end and auxiliary fans), the heat effects from the hot air plume rising from the nozzle, and the potential particle emission such as the release and movement of chopped fibers in the air. The effects on airflow of the tool head shroud during experimental testing should also be considered. The environment of the printer plays a role in this potential modeling, including enclosure type and ambient airflow through the enclosure. As expected, this problem is complex and thereby addresses a gap in literature in understanding the hidden health and printing consequences of using fiber reinforced materials on desktop FFF machines. This work shows clear qualitative results in the exposure of chopped fibers and providing quantitative results through proper modeling and further experimental testing can support these initial findings.

5. Conflicts of interest

The author declares no conflicts of interest related to the research and findings presented in this paper.

6. Statement on generative artificial intelligence (AI) usage

In the preparation of this manuscript, Google Gemini was used solely for language editing purposes. The tool was applied for grammar refinement and clarity improvement, and all AI-generated content has been thoroughly reviewed and edited by the author to ensure originality and accuracy. I, the author, affirm full authorship of the final text and accept complete responsibility for its content.

7. Compliance with standards of research involving human participants

All research activities involving human participants complied with the ethical requirements of institutional, provincial, and national review bodies, and other applicable guidelines. Informed consent was secured from the study participant.

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