

Extrusion Processing Conditions of Copper Fiber-Reinforced PLA Filaments: Influence of Extrusion System and Fiber Loading on Stability and FFF Printability

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Abstract

Poly(lactic acid) (PLA) is widely used in fused filament fabrication (FFF); however, its limited thermal and mechanical performance restricts broader application. In this study, PLA was compounded with fine cut copper fibers to investigate the effect of metal fiber content on filament extrusion behavior, with a focus on melt flow stability and filament diameter consistency. Copper fibers with a diameter of 0.05 mm and an average length of 1.2 mm were incorporated at 5 - 60 wt.%. Filaments with target diameters of 1.75 mm and 2.85 mm were produced using two different extruders with real-time optical diameter monitoring, and processing parameters were optimized for each composition. All formulations were successfully extruded, although increasing fiber content resulted in greater sensitivity of filament diameter to processing conditions. Diameter variations of 1.5–2.0 mm and 2.7–2.9 mm were observed for 1.75 mm and 2.85 mm filaments, respectively. Pyrolysis analysis confirmed good agreement between intended and actual copper fiber contents. Among the filaments produced using the 3devo Composer 450 extruder, the formulation containing 5 wt.% copper fibers with a diameter of 2.85 mm exhibited the highest dimensional stability and was successfully printed using a commercial Ultimaker 2+ system. In comparison, the ARTME Desktop Filament Extruder produced filaments with more consistent diameters across the investigated composition range, and all formulations containing up to 40 wt.% copper fibers were successfully printed, demonstrating the improved printability achievable with this extrusion system.

Keywords: Poly(lactic acid), Copper Fibers, Composite Filaments, Extrusion Processing, Filament Diameter Stability

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1. Introduction

The increasing environmental concerns associated with greenhouse gas emissions, plastic pollution, and the depletion of fossil resources have accelerated the transition toward sustainable materials in polymer processing and manufacturing [1-3]. Among biopolymers, polylactic acid (PLA) has emerged as one of the most widely studied and commercially relevant alternatives to petroleum-based polymers [4]. PLA offers desirable characteristics such as good strength, ease of processing, and compatibility with

renewable resource streams, making it central to the development of bio composites used in packaging, consumer products, and additive manufacturing [5, 6].

Despite its advantages, PLA exhibits limited thermal stability, brittleness, and low heat resistance, which restricts its applicability in high-performance or thermally demanding environments [7]. To mitigate these limitations, numerous studies have focused on reinforcing PLA with fibers or particulate fillers that enhance stiffness, modify crystallinity,

and improve thermal performance [8-10]. Natural fibers have been widely explored for these purposes; however, their hydrophilic nature, variability, and limited thermal stability complicate uniform dispersion and reliable processing, particularly in fused filament fabrication additive manufacturing, where PLA is a suitable material due to its low melting temperature and stable rheological behavior, requiring consistent filament diameter and melt flow for process stability [11].

In recent years, attention has expanded toward the integration of metal-based reinforcements into polymer matrices, driven by their potential to improve thermal conductivity, mechanical robustness, and overall composite performance [12, 13]. Copper offers high thermal conductivity, good mechanical strength, favorable interfacial behavior in polymer systems and is fully recyclable. These properties make copper an attractive candidate when the goal is to enhance heat transfer during melt processing, influence crystallization behavior, or improve structural stability under load [14, 15].

While various copper-containing additives such as powders, oxides, salts, and microspheres have been incorporated into polymers, their application in extrusion-based processing often introduces challenges [16]. Finely dispersed powders are prone to agglomeration, uneven distribution, and sedimentation in the melt, leading to unstable flow behavior and fluctuations in filament diameter during extrusion [17]. The high surface area of powders can also excessively increase melt viscosity, complicating filament formation and reducing processing reliability [18]. Furthermore, spherical or irregularly shaped particles do not contribute significantly to reinforcement and often act merely as passive fillers within the polymer matrix [19].

In contrast, copper fibers exhibit morphological and processing advantages that make them particularly suitable for extrusion-based compounding and filament production. Their elongated geometry promotes more uniform distribution within the melt and reduces the tendency to form agglomerates [20]. Fibers remain more stable in the melt due to reduced sedimentation effects, helping maintain a consistent filler content along the filament length [21]. From a functional perspective, copper fibers facilitate more efficient heat conduction pathways through the composite, which can lead to more uniform melt temperatures, improved crystallization behavior of PLA, and more stable extrusion dynamics [22]. Additionally, their reinforcing geometry can contribute to mechanical performance in ways that spherical particles cannot [23].

Maintaining a stable filament diameter is essential for reliable printing performance, dimensional accuracy, and process repeatability. Variations as small as ± 0.05 mm can lead to over-extrusion, under-extrusion, clogging, or weakened mechanical properties in 3D-printed parts [24, 25]. While several studies have examined natural fiber-reinforced PLA for additive manufacturing, very few have investigated metal-fiber-reinforced PLA, and even fewer have evaluated how different fiber weight percentages affect filament extrusion stability, particularly with respect to diameter consistency.

Previous studies have investigated copper- and metal-reinforced PLA composites for additive manufacturing, with a primary focus on the mechanical, thermal, or electrical properties of the printed parts. However, limited attention has been given to the extrusion behavior of short copper-fiber-reinforced PLA, particularly regarding filament diameter stability over a wide range of copper contents. In addition, a direct comparison of different filament extrusion systems and their influence on the processability and printability of highly filled PLA-copper fiber composites remain limited. In this study, PLA was compounded with varying weight percentages of copper fibers to investigate how fiber content affects filament extrusion behavior, specifically focusing on melt flow stability and the consistency of the filament diameter. By examining these parameters, the study aims to identify the optimal copper fiber loading that maintains reliable processability while introducing desirable thermal and mechanical influences on the material. The findings contribute to the development of advanced PLA-based composite filaments tailored for additive manufacturing applications where print stability, structural performance, and thermal behavior are critical.

2. Materials and Methods

2.1. Copper Fibers

The fibers were produced by AERUMTEC GmbH (Germany) from oxygen-free copper (OF) wire with an initial diameter of 8 mm. The wire underwent multiple drawing processes until a nominal final diameter of 0.05 ± 0.002 mm was achieved. Subsequently, the mechanical characterization of the wires was carried out using a universal testing machine of the type *ZwickRoell testControl II*, according to DIN EN ISO 6892-1.

When interpreting the results, it must be considered that the very small specimen dimensions caused the accuracy class of the installed load cell to be undershot. The measurements obtained should therefore be regarded with appropriate caution. Tensile strengths of up to 591.8 ± 9.8 MPa and elongations of 0.34 ± 0.12 % were recorded. The high strength values combined with the low ductility are attributed to the pronounced plastic deformation during the cold-drawing process without subsequent heat treatment, which leads to significant elongation and strain hardening of the copper microstructure.

To improve handling, the individual wires were subsequently braided. The braiding process resulted in a plaited structure comprising a total of 512 individual wires (Figure 1, left). This braided structure was then separated into defined fiber lengths of 1.2 mm using an in-house developed separation device in a shear cutting operation. Due to the high flexibility of the braid, the structure was held in position using a guide pipe to ensure a defined fiber cut (Figure 1, middle). Before compounding, the fibers were examined using optical microscopy to verify the uniformity of their geometry, assess the distribution of fiber lengths, and check for damage or contamination originating from the cutting process. The

resulting micrograph (Figure 1 (right)) illustrates the morphology of the fibers and confirms their suitability for incorporation into the PLA matrix.



Figure 1. Copper fibers by AERUMTEC GmbH (Germany) produced out of a round braided copper (left) and subsequently cut and (middle) used in this research, (right) Microscopy photo from fibers

2.2. Polymer Matrix

The polymer matrix consisted of polylactic acid (PLA) granulates, by Ingeo™ 4043D, NatureWorks LLC, purchased from 3devo (The Netherlands). The material is a commercially available extrusion-grade PLA recommended for processing at temperatures between 150–240 °C. The granules were used as received, without pre-drying or modification, to reflect typical processing conditions in filament production. Visual inspection of the granules (Figure 2) confirmed their uniform size and translucency, which is important for ensuring consistent melting behavior within the extruder. PLA was selected due to its biodegradability, wide use in fused filament fabrication (FFF), and compatibility with copper-based fillers.



Figure 2. PLA granulates by Ingeo™ 4043D, NatureWorks LLC

2.3. Copper Fiber Loadings

Six different filler loadings were prepared: 5 wt.%, 10 wt.%, 15 wt.%, 20 wt.%, 40 wt.%, and 60 wt% of copper fibers. These compositions were chosen to study the influence of filler loading on both processability and diameter stability during filament extrusion. In addition to weight fractions, the corresponding volume fractions were calculated, since fiber–polymer interactions and mechanical behavior are more directly related to volumetric composition. A detailed table of mass and volume fractions is provided in Table 1. The conversion from weight percentage to volume percentage was calculated using the standard relation:

$$Vol.\% = \frac{\frac{w}{\rho_{Cu}}}{\frac{w}{\rho_{Cu}} + \frac{100-w}{\rho_{PLA}}} \times 100 \quad (1)$$

Where w , represents the weight percentage of copper fibers. This formula accounts for the significant density difference between copper and PLA, which strongly influences the resulting filament structure.

Table 1. Copper weight percentages and their equivalent volume percentages

Cu Fiber wt.%	Cu Fiber Vol.%
5	0.715
10	1.485
15	2.316
20	3.211
40	8.447
60	17.190

Filament was extruded at 2.85 mm diameter for all compositions. Additionally, filaments of 1.75 mm diameter were produced for the 5 wt.% and 10 wt.% samples to evaluate whether lower filler contents allow stable processing at smaller diameters commonly used in FFF printing.

2.4. Extrusion System

3devo Composer 450

Compounding and filament extrusion for 5 - 20 wt% were performed using a 3devo Composer 450 single-screw extruder. The device is equipped with a screw capable of operating between 0-15 RPM, enabling precise control of material throughput. The extruder features four independently controlled heating zones, which allow fine adjustment of the temperature gradient along the barrel to accommodate changes in melt viscosity resulting from different fiber loadings.

The system also includes an optical filament measurement unit with an accuracy of $\pm 10 \mu\text{m}$, used to monitor the filament diameter in real time. This feature was essential for maintaining stable filament dimensions and evaluating how filler content affects diameter fluctuations. The extruder is shown in Figure 3.



Figure 3. 3devo Composer 450 single-screw extruder at Ansbach University of Applied Sciences

ARTME Desktop

In addition, the compounds containing 10–60 wt% Cu were extruded using an ARTME Desktop Filament Extruder. The extruder provides a screw speed range of 0–25 RPM and supports the production of 1.75 and 2.85 mm filaments. The 10–20 wt% formulations were re-extruded, while 40 wt% and 60 wt% formulations were processed for the first time using this system, allowing the extrusion behavior to be evaluated over a wider range of copper contents. All filaments were extruded with a diameter of 2.85 mm. Figure 4 depicts the second extruder.



Figure 4. ARTME Desktop extruder at Ansbach University of Applied Sciences

2.5. Filament Production Method

PLA granules and copper fibers were premixed manually in a container to ensure initial homogenization before extrusion. The dry blend was then introduced into the extruder hopper. Since copper fibers have a higher density than PLA, the mixture was stirred repeatedly during feeding to minimize sedimentation and maintain a consistent composition throughout processing.

Inside the extruder, the materials were melted, mixed, and conveyed through the screw before being pushed through a circular nozzle. The extruded filament was subsequently cooled by ambient air and the extruder's cooling fan before being guided through the optical sensor.

2.6. Filament Diameter Control and Stability Criteria

Maintaining a consistent filament diameter is critical for 3D printing performance; therefore, a strict diameter control protocol was used. For filaments with a target diameter of 1.75 mm, the acceptable tolerance window was 1.65–1.80 mm. For 2.85 mm filaments, the acceptable window was 2.70–2.90 mm. Although the measured diameter fluctuations are larger than typical commercial filament tolerances, the produced filaments remained printable under adjusted printing parameters, allowing the evaluation of their extrusion behavior.

During extrusion, diameter fluctuations were corrected by adjusting:

- The manual puller speed, which directly influences filament stretching,
- The heater temperatures, which control the melted viscosity and flow behavior,
- The fan speed, which affects the cooling rate and thus the final diameter, and
- The extruder RPM, which influences the material flow rate.

Diameter data from the optical sensor were continuously monitored, allowing fine real-time adjustments. All filaments were coiled on spools after reaching diameter stability and allowed to cool to room temperature. The filament diameter data were used to evaluate the dimensional stability of the produced filaments. The mean diameter and standard deviation were calculated for each formulation. The percentage of measurements within the defined tolerance range was also considered as an indicator of dimensional stability.

3. Results

3.1. Optimized Extrusion Parameters

Because the copper fibers significantly alter melt viscosity and thermal conductivity, the extrusion parameters had to be optimized for each composition. Adjustments were made to:

- RPM (to balance throughput and mixing),
- Temperature of all heaters (to ensure full melting without thermal degradation),
- Manual puller speed (for diameter tuning),
- Cooling fan percentage (to stabilize the solidification process).

The final optimized settings for each copper content are summarized in Table 2 and 3, and these parameters were used for all subsequent experiments. Figures 5 and 6 also show the microscopy pictures for each extruded filament.

Table 2. Optimized settings for ARTME extruder with different copper content and diameter

Photo (Fig. 6)	Weight Percentage (%)	Heater (°C)	Extruder Speed (RPM)	Puller Speed (rpm)	Fan Speed (%)
a	10	161	7.5	20	100
b	20	161	9	20	100
c	40	161	11	20	100
d	60	161	13	20	100

Table 3. Optimized extrusion parameters for the 3devo Composer 450

Photo (Figure 5)	Filament Diameter (mm)	Weight Percentage (%)	Heater 1 (°C)	Heater 2 (°C)	Heater 3 (°C)	Heater 4 (°C)	Extruder Speed (RPM)	Puller Speed (Ticks)	Fan Speed (%)
b	1.75	5	190	215	225	230	2.5	1400	40
c	2.85	5	190	215	225	230	4.6	1160	50
a	1.75	10	200	215	225	230	3	1100	30
d	2.85	10	190	215	225	230	4.3	1160	50
e	2.85	15	190	215	225	230	4.3	1000	50
f	2.85	20	190	215	225	230	5	1000	51

The measured filament diameters showed that dimensional stability was influenced by both copper fiber content and the extrusion system. In general, higher copper fiber contents resulted in greater sensitivity to processing conditions. Quantitative diameter measurements were therefore used to compare the dimensional stability of the different formulations and extrusion systems. Among the tested samples in 3devo, the filament containing 5 wt.% copper fibers (2.85 mm) exhibited the most stable extrusion behavior and the most consistent diameter. As a result, it was the only formulation that allowed successful and stable printing under the tested conditions. In addition, the ARTME Desktop Filament Extruder produced filaments with more consistent diameters than the 3devo Composer 450 throughout the investigated composition range. This improved dimensional stability resulted in enhanced printability, with all filaments containing up to 40 wt% Cu being successfully processed by FFF printing. An Ultimaker 2+ 3D printer (Figure 7), a commercially available desktop FDM system designed for 2.85 mm filaments, was used to print the fabricated filaments, thereby demonstrating the practical printability of the extruded PLA–copper fiber composites under standard printing conditions. However, the printing conditions were not identical for both extrusion systems, particularly regarding nozzle diameter.

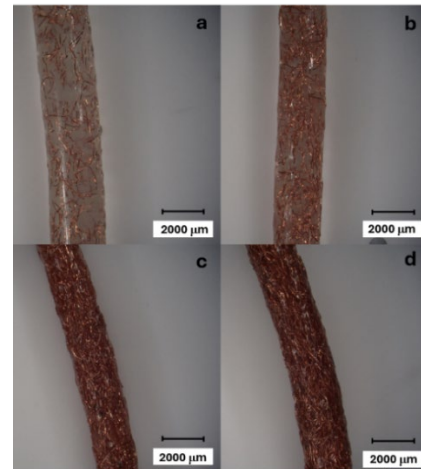


Figure 5. Filament microscopy pictures with ARTME extruder (diameter of 2.85 mm): a) 10 wt.%, b) 20 wt.%, c) 40 wt.%, d) 60 wt.%

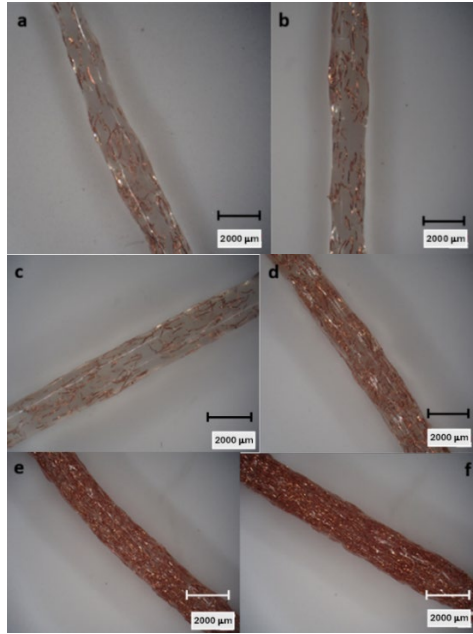


Figure 6. Extruded filament microscopy pictures with 3devo extruder and different copper content and diameter: **a)** 10 wt.% - 1.75 mm, **b)** 5 wt.% - 1.75 mm, **c)** 5 wt.% - 2.85 mm, **d)** 10 wt.% - 2.85 mm, **e)** 15 wt.% - 2.85 mm, **f)** 20 wt.% - 2.85 mm

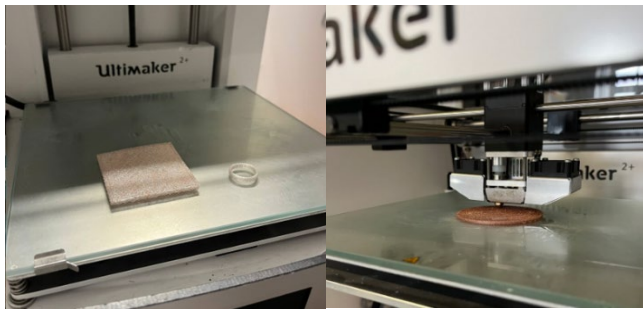


Figure 7. Printed parts by the filament with a diameter of 2.85 mm and weight percentage of 5% extruded by 3devo (left), and 40% extruded by ARTME (right)

The printing tests were performed using a layer height of 0.2 mm, wall thickness of 1.6 mm, and an infill density of 20% with a grid pattern. The printing temperature was set to 200 °C, while the build plate temperature was maintained at 60 °C. A printing speed of 40 mm/s was used, and the cooling fan was set to 100% to ensure proper solidification of the extruded material. Also, the diameter of the nozzle was 0.4 mm for 5 wt% filament, extruded by 3devo extruder and 0.8 mm for the filaments which extruded by ARTME extruder. Figure 8 also presents details of the printed part obtained by microscopy.

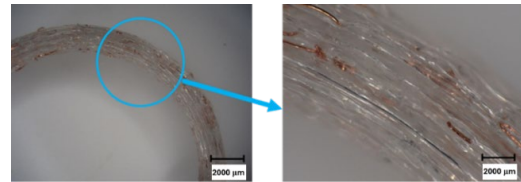


Figure 8. Microscopy pictures of the printed rotationally symmetric part [26]

3.2. Pyrolysis Analysis

To evaluate fiber distribution within the extruded filaments, a pyrolysis-based dispersion analysis was conducted. Sections of filaments were cut and placed in a high-temperature furnace for 2 hours at a temperature of 600 °C, where they were heated until all PLA material had decomposed and volatilized. The remaining copper fibers were then collected and analyzed. The remaining copper mass was weighed and compared with theoretical values derived from the initial formulation. This allowed identification of possible segregation or fiber loss during extrusion.

Representative images of pyrolyzed filament samples (Figure 9) are provided, and detailed calculations of fiber recovery efficiency and distribution uniformity are shown in Table 4:

Table 4. Detailed pyrolysis analysis calculations regarding distribution of copper fibers

Related Photo	Filament Diameter (mm)	Primary Weight Percentage (%)	Weight of the Fiber (g)	Weight of the Filament (g)	Cu Weight Percentage (%)
Fig. 5 (a)	1.75	10	0.3174	0.3367	9.43
Fig. 5 (d)	2.85	10	0.1013	1.0046	10.10
Fig. 5 (c)	2.85	5	0.0351	0.7961	4.40
Fig. 5 (b)	1.75	5	0.0137	0.2950	4.60
Fig. 5 (e)	2.85	15	0.0922	0.5818	15.80
Fig. 5 (f)	2.85	20	0.2336	1.0904	21.24
Fig. 6 (a)	2.85	10	0.0347	0.3762	9.22
Fig. 6 (b)	2.85	20	0.1398	0.6558	21.32
Fig. 6 (c)	2.85	40	0.5381	0.1664	32.33

Fig. 6 (d)	2.85	60	0.3388	0.7173	47.23
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The pyrolysis results showed good agreement between the nominal and measured copper contents for the 5–20 wt.% formulations. At higher nominal loadings, deviations became more pronounced. For the formulations with nominal copper contents of 40 wt.% and 60 wt.%, the measured copper contents were 32.33 wt.% and 47.23 wt.%, respectively. These deviations indicate that maintaining the intended copper concentration becomes more challenging at high fiber loadings.



Figure 9. Pyrolysis analysis result for the filaments

4. Conclusion

The present study investigated the extrusion behavior of PLA reinforced with cut copper fibers over a wide range of copper loadings (5–60 wt.%), with particular emphasis on melt flow stability, filament diameter consistency, and printability for fused filament fabrication (FFF). All investigated formulations were successfully compounded and extruded into 2.85 mm filaments, while 1.75 mm filaments were additionally produced for the 5 wt.% and 10 wt.% compositions. The results demonstrate that copper fibers can be incorporated into PLA at relatively high filler contents using conventional filament extrusion systems, although increasing fiber loading leads to greater sensitivity of filament diameter to processing conditions.

Optimization of the extrusion parameters, including screw speed, puller speed, temperature, and cooling conditions, enabled the production of filaments with acceptable dimensional stability despite the increased melt complexity introduced by the copper fibers. Pyrolysis analysis showed good agreement between the intended and measured copper contents for the lower filler loadings (5–20 wt.%), indicating good agreement between the nominal and measured copper contents. In contrast, the 40 wt.% and 60 wt.% formulations exhibited noticeable deviations from their target copper contents, suggesting reduced compositional accuracy at higher fiber loadings, likely due to challenges associated with feeding and maintaining a homogeneous distribution of the high-density copper fibers during extrusion.

Among the filaments produced with the 3devo Composer 450 extruder, the 5 wt.% copper fiber

formulation with a nominal diameter of 2.85 mm exhibited the highest dimensional stability and the best overall printability. In comparison, the ARTME Desktop Filament Extruder produced filaments with more consistent diameters across the investigated composition range, enabling successful FFF printing of all formulations containing up to 40 wt.% copper fibers. These results demonstrate that the choice of extrusion system has a significant influence on filament quality and printable filler loading.

The findings confirm that copper fiber-reinforced PLA filaments can be processed successfully over a broad range of compositions and that stable filament production is achievable through appropriate optimization of extrusion parameters. While maintaining the intended fiber content becomes increasingly challenging at very high copper loadings, the results demonstrate the feasibility of producing printable copper fiber-reinforced PLA filaments containing up to 40 wt.% Cu using a conventional FFF workflow. This work provides a practical basis for the development of metal fiber-reinforced PLA filaments for additive manufacturing and establishes a foundation for future investigations into the thermal, mechanical, and functional properties of the printed composites.

In practical applications, PLA-copper fiber composite filaments exhibit promising potential for the fabrication of functional components using fused filament fabrication (FFF). The incorporation of copper fibers has the potential to influence the mechanical, thermal, and electrical behavior of the resulting composites. However, these properties were not experimentally characterized in the present study and therefore require further investigation. The demonstrated printability using conventional FFF equipment highlights the feasibility of processing such composites within existing additive manufacturing workflows.

Overall, the results indicate that PLA filaments with fillers (e.g. copper fiber) can contribute to broadening the application range of FFF technology, moving beyond purely structural or decorative components. With further optimization of material formulation and processing parameters, these composites could support the development of application-specific, functionally enhanced filaments, reinforcing the role of FFF as a manufacturing technology for advanced and customized engineering parts.

Future work will include mechanical and electrical characterization of the printed parts, such as tensile and conductivity testing, to evaluate the influence of copper fiber reinforcement on the performance compared to conventional PLA. Quantitative image analysis may also be planned to investigate fiber orientation and its effect on the properties of the composite filament.

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