Reinforcing 3D Printed Polymers with Continuous Stainless Steel Fiber Bundle

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Abstract

Recently, fused filament fabrication 3D printing (FFF) has become a more widely applied technology for producing prototyped and use components. Therefore there is large interest in enhancing the mechanical properties of these parts. One such way of improving these properties is through the use of a polymer composite which effectively adds reinforcement fibers to the filament [1].

The goal of this project is to investigate for the first time the feasibility of 3D printing continuous steel fiber ex-situ in a nylon matrix and evaluate its material characteristics. This involved both the fabrication of steel reinforced nylon filaments along with the printing of parts using these filaments.

Methodology

Natural Arkema Polyamide 11 (Nylon)

Stainless Steel Fiber (SSF)

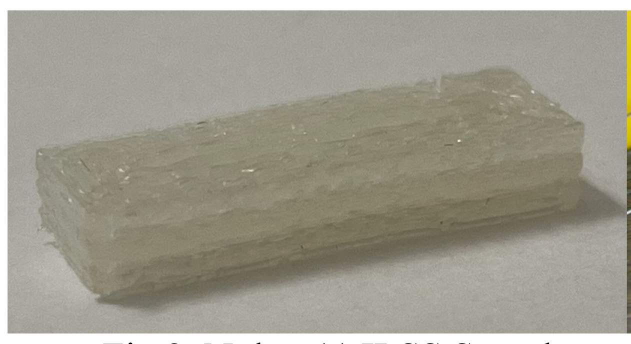


Fig 2. Nylon 11 ILSS Sample

Fig 3. Continuous SSF Spool

Engineering Polymer: [2]
Melting Temp: 201 °C
Degradation Temp: 350 °C

Continuous Fiber Bundle:
90 Fibers
Diameter 14µm

Methodology

A 3Devo Filament Extruder (3Devo) is used to extrude the filament. Pellets, placed in the hopper, were then heated up in four stages through the extruder screw before coming out the nozzle to be cooled and wound onto a spool for printing (4). The temperatures of the heating zones had to be experimentally determined for each material and adjusted for the environment. Slight modifications were made to the set-up in to extrude filament containing continuous steel fibers.

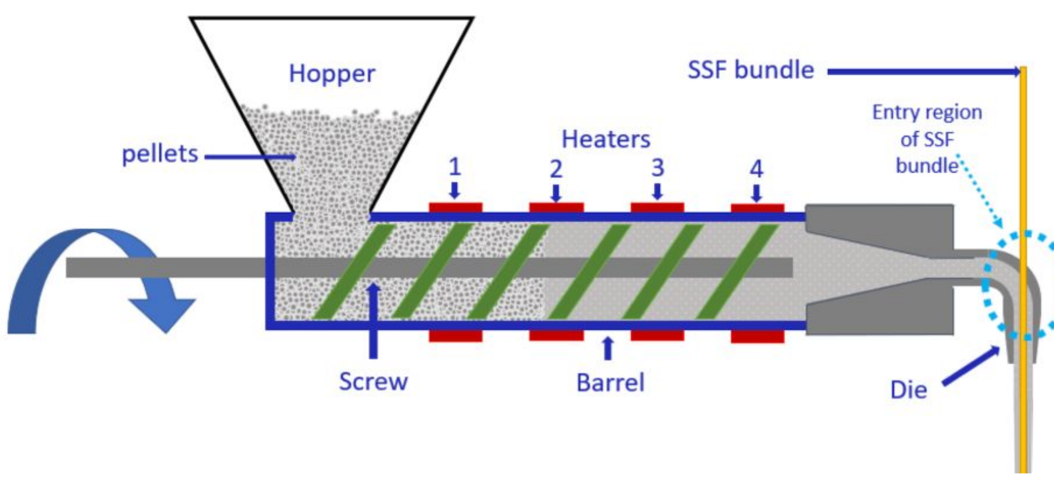


Fig 4. The Inside of 3Devo

A pyrometer was used to capture thermal imaging of the system (5) where the hottest part was the nozzle temperature (6). The filament is also quite hot because the SSF acted as a conductor while the cooling fans were aimed at the outside of the filament.

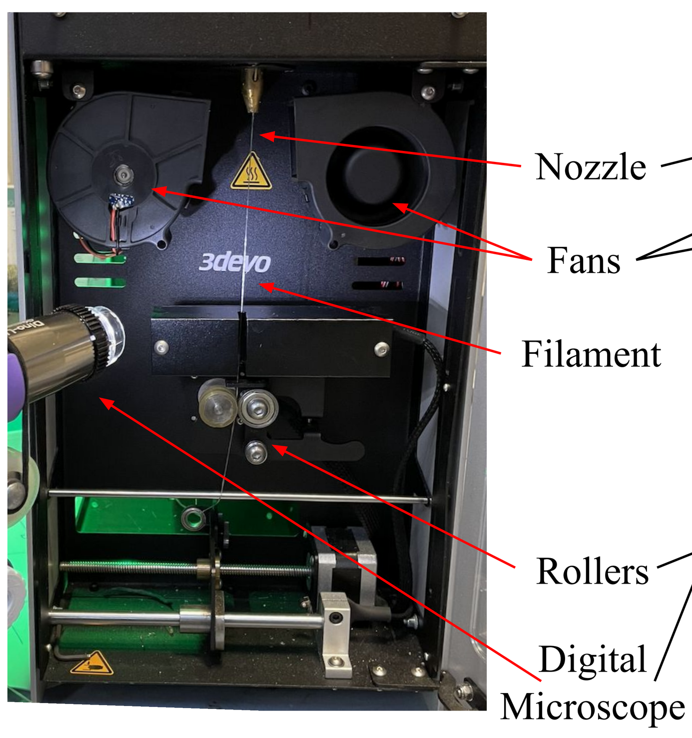


Fig 5. Continuous Fiber Experimental Set-Up

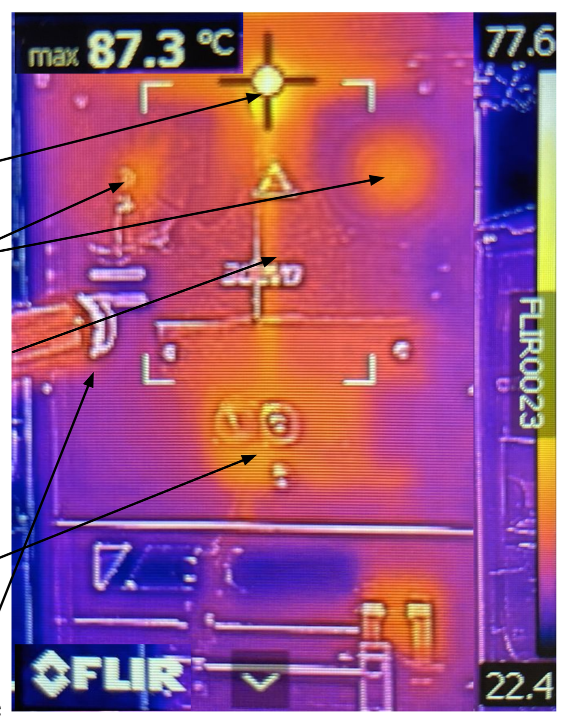


Fig 6. Thermal Imaging of Continuous Fiber Extrusion

The quality of the filament was heavily influenced by the temperature. A margin of error of ±2 degrees Celsius was determined before the extrusion would fail.

Filament Analysis

Extrusion parameters were determined from the material data and experimentally. PLA SSF filament was previously fabricated to understand the extrusion process.

Material	RPM	Fans	H4	H3	H2	H1
Nylon	2.5	78%	231	235	240	225
Nylon Cotton	2.0	26%	238	243	248	243
Nylon SSF	2.0	40%	238	242	245	239

Table 1. Table of Extrusion Parameters of Nylon

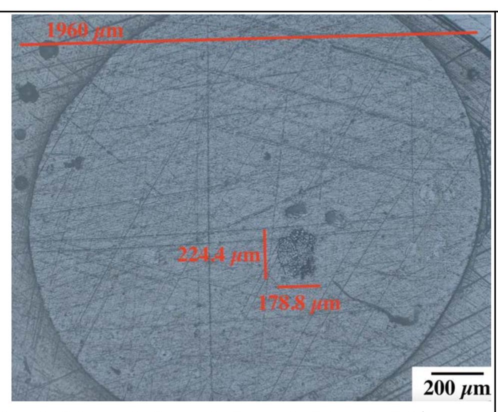
The goal as extrusion progressed was to reduce diameter, thus reducing volume fraction, and evaluate impregnation. Volume fraction was calculated using Equation 1.

$$Volume\ Fraction\ (\%) = 100\% \times \frac{V_{SSF}}{V_{Total}} \quad \text{Eq 1.}$$

Nylon with Cotton Fibers | **Nylon with SSF**

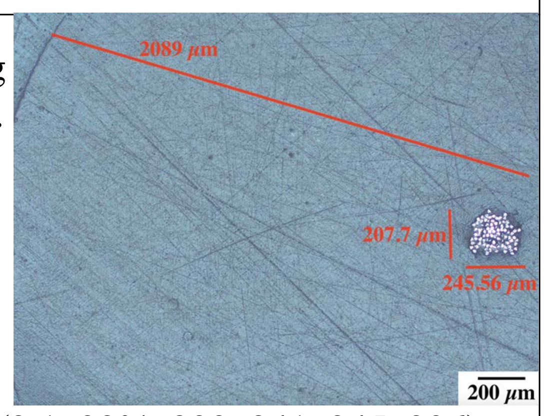
Initial filaments resulted in large diameters and low volume fractions.

Fig 7.



(2.0, 35%, 251, 254, 258, 252)
Diameter: 1.96 mm
VF = 1.1%

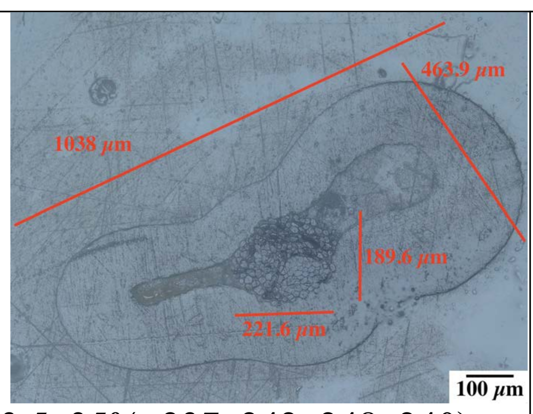
Fig 10.



(2.1, 32%, 233, 241, 245, 236)
Diameter: 4.18 mm
VF = 0.025%

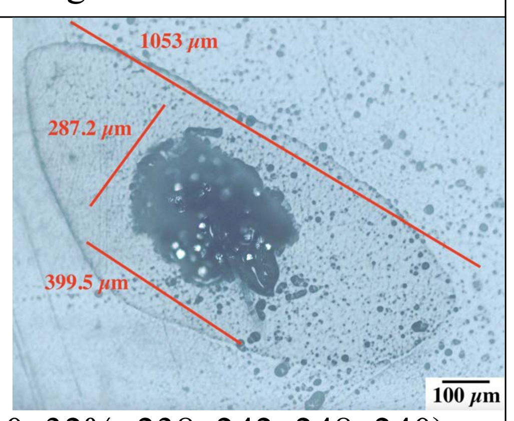
Slow Nylon cooling cormed oblong shaped filament, due to the pullers flattening the hot Nylon instead of pulling down to diameter.

Fig 8.



(3.5, 35%, 237, 242, 248, 240)
Diameter: 0.47 mm - 1.04 mm
VF = 8.7%

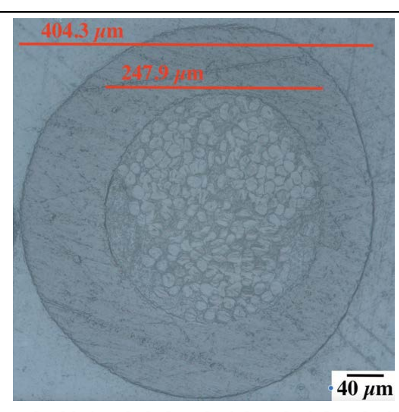
Fig 11.



(2.0, 32%, 238, 242, 248, 240)
Diameter: 0.8 mm - 1.05 mm
VF = 0.52%

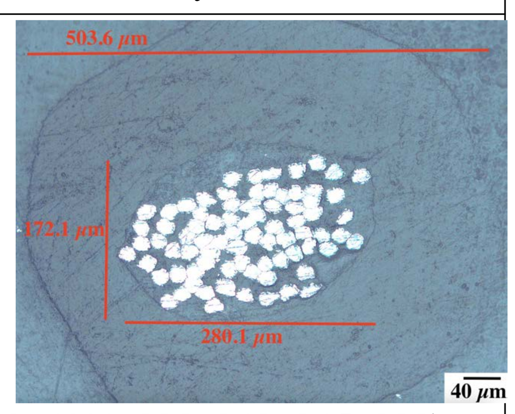
A filament diameter of ~0.5 mm was successfully achieved.

Fig 9.



(2.0, 26%, 238, 243, 248, 243)
Diameter: 0.4 mm
VF = 38%

Fig 12.



(2.0, 40%, 238, 242, 245, 239)
Diameter: 0.52 mm
VF = 1.62%

Parameters in form of (RPM, Fans, H4, H3, H2, H1)

Next, Interlaminar Shear Stress Testing (ILSS) was conducted according to standard ASTM D2344 [3]. The Nylon never reached its ultimate stress point and instead underwent mostly elastic deformation (13-15).

Fig 13. Initial Set-Up

Fig 14. Max Deflection

Fig 15. After Release

Nylon 11 was determined to have a shear stress of 5.3 MPa [±0.5] using Equation 2 (16).

$$F_{abs}(MPa) = 0.75 \times \frac{P_m}{b \times h} \quad \text{Eq 2.}$$

Microscope analysis of the samples (17-18), show in the red box that the bottom layer failed under tension.

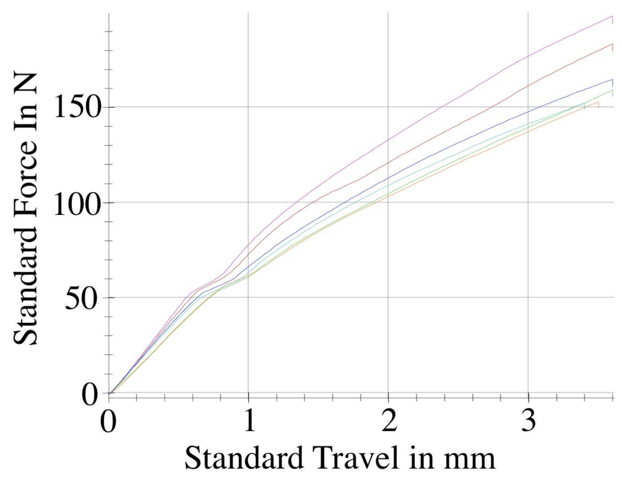


Fig 16. Nylon ILSS Samples

Fig 17. Before ILSS Testing

Fig 18. After ILSS Testing

FFF 3D Printing

In addition to extrusion parameters, printing Nylon has more challenges than PLA. Problems include, bed adhesion, warping, under extrusion and inconsistencies in the Nylon-SSF filament diameter. After printing multiple Nylon calibration Cubes (19), a fiber sandwich was printed (20). This was done to test the polymer matrix impregnation by printing layers of Nylon, placing a layer of steel fiber, and then continuing to print over this layer.

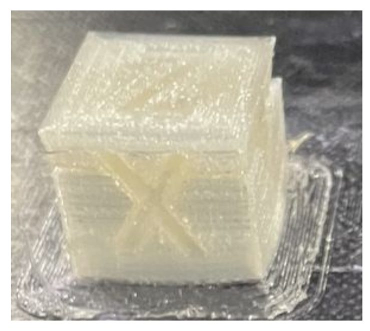


Fig 19. Nylon Calibration Cube

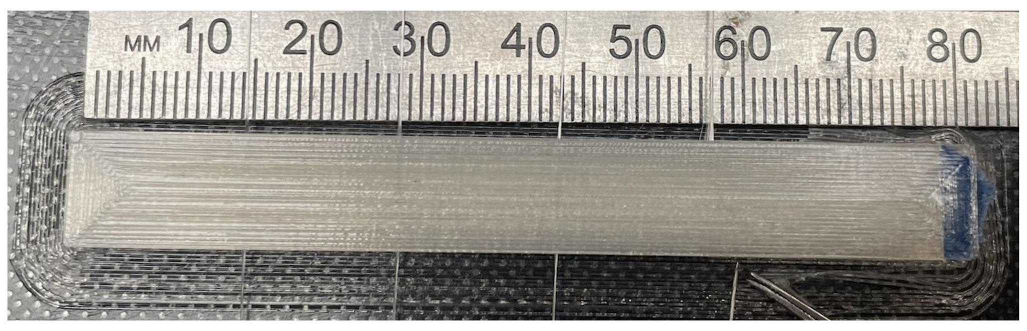


Fig 20. Fiber Sandwich

Lastly, two layers of Nylon with SSF was printed to observe the cross section of the printed segment (21).

Fig 21. Fused Filament Fabrication of Nylon with SSF

When looked at under a microscope (22), the zoomed in version (23) shows good fiber impregnation and no large air gaps.

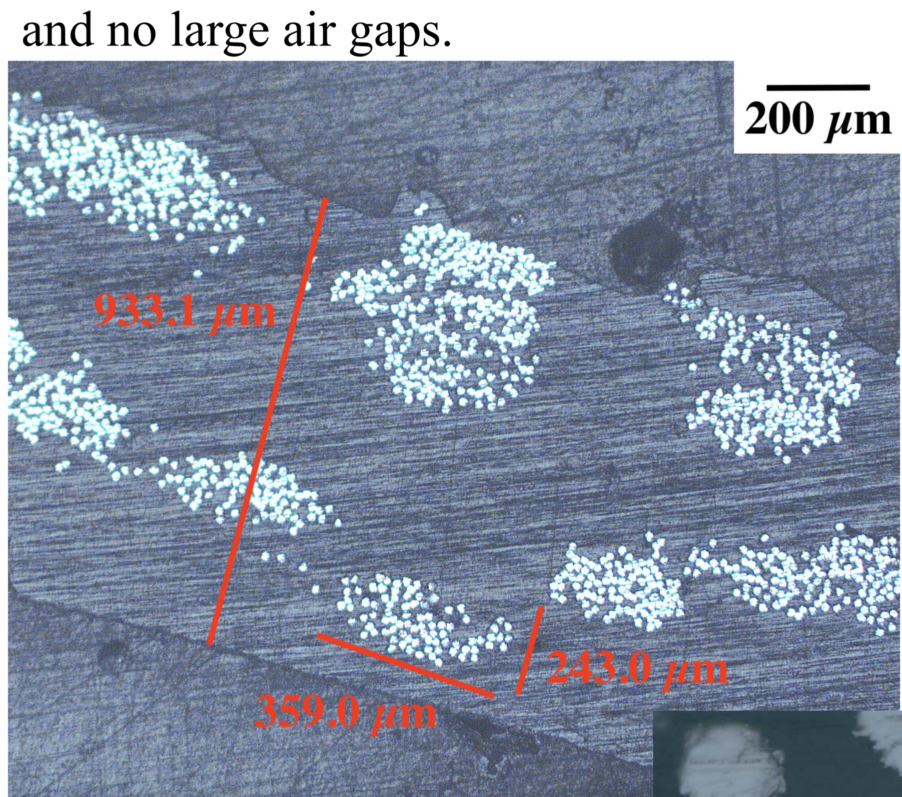


Fig 22. Cross Section of 3D Printed Nylon with SSF

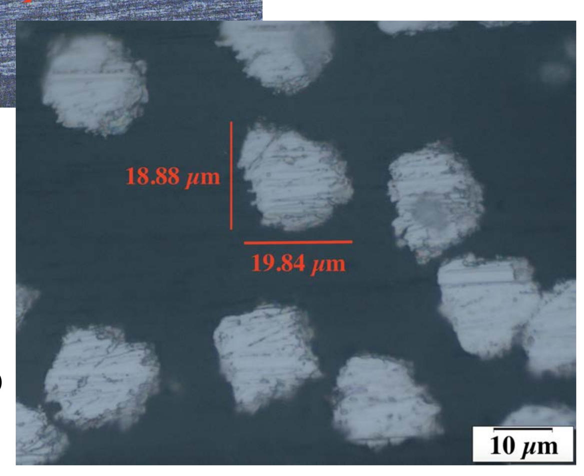


Fig 23. Cross Section of 3D Printed Nylon with SSF

Conclusion

A Stainless Steel Fiber bundle was successfully embedded into the center of the Nylon matrix material to produce a 3D printable filament with a diameter of 0.5 mm and a volume fraction of 1.8%. This material was then printed to show good fiber impregnation.

References

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[1] A. N. Dickson, J. N. Barry, K. A. McDonnell, and D. P. Dowling, "Fabrication of continuous carbon, glass and Kevlar fibre reinforced polymer composites using additive manufacturing," *Additive Manufacturing*, vol. 16, pp. 146–152, Aug. 2017, doi: 10.1016/j.addma.2017.06.004.

[2] "Nylon 11 / PA 11," *Xometry Europe*. https://xometry.eu/en/materials/nylon-pa11/

[3] D30 Committee, "Test Method for Short-Beam Strength of Polymer Matrix Composite Materials and Their Laminates," ASTM International. doi: 10.1520/D2344_D2344M-22.