Flexible Fusion 3D: Advancing Additive Molding Fabrication for Enhanced Mechanical Properties of FDM Parts

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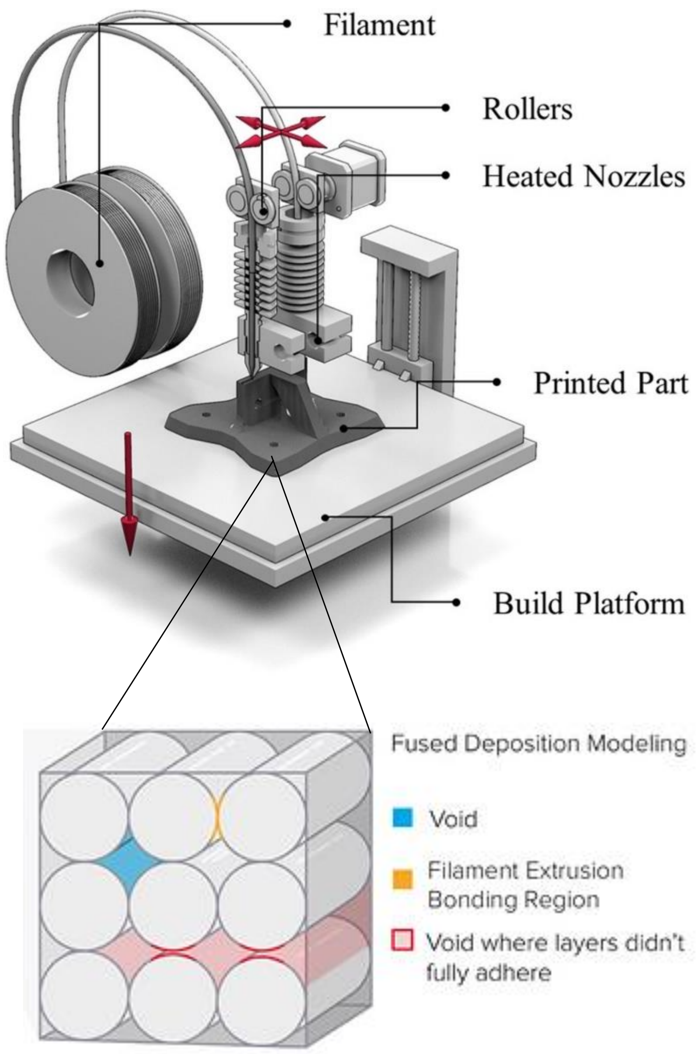
Introduction

- Fused Deposition Modeling (FDM) is an additive manufacturing technology that constructs objects by extruding thermoplastic materials layer-by-layer.

FDM Prints defects:

- **Inadequate fusion bonding** between layers
- Presence of substantial **thermal residual stresses**
- Compromise their **mechanical performance** and dimensional accuracy.
- Inherent anisotropy limits its applicability to a **quasi-2.5D technique**

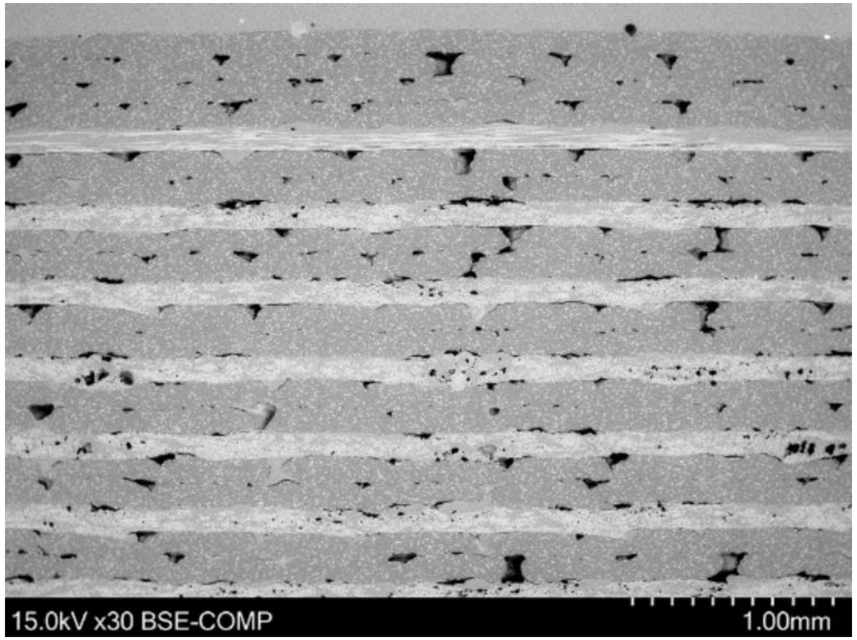


Ref. Samia Adil| Ismail Lazoglu, ,A review on additive manufacturing of carbon fiber-reinforced polymers: Current methods, materials, mechanical properties, applications and challenges

State-of-the-Art SCF/LCF FDM Printing Technology

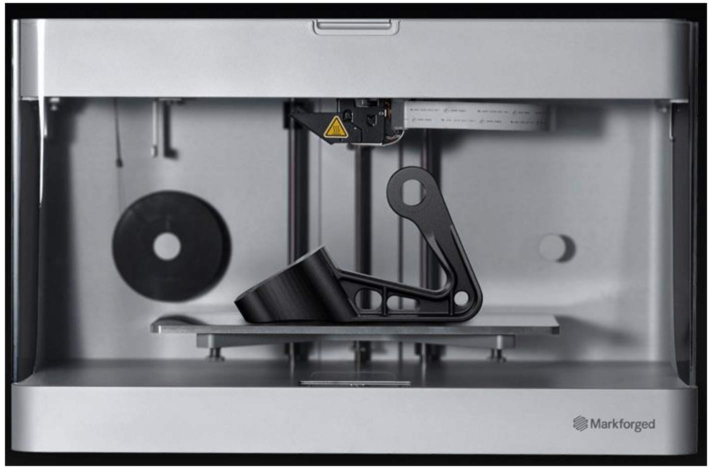
COMPOSITES MODELING AND MANUFACTURING LAB

- Current FDM printer can print:
  - Nylon (PA-6) short carbon fibers (**SCF**) with **10.5% volume fraction**
  - Nylon (PA-6) long carbon fibers (**LCF**) with **45 % volume fraction**



Micrographs of SCF/LCF


DM Micro AFP 3D printer



MarkForged Mark 2

Ref. https://sites.wp.odu.edu/cmsl/lab-facilities/

Flexible Fusion 3D (FF3D)

- **FDM:** Desktop Metal Fiber and MarkForged Mark 2.
- **Talc Powder Compaction:** 10 minutes before and after heating, applying 2-4 tons of pressure
- **Mold Heating and Compaction**: A 2-hour non-equilibrium heating process at (initial set temperature) 260°C.

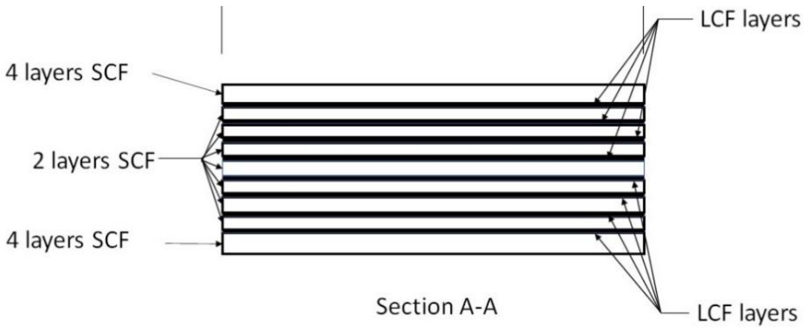
FDM

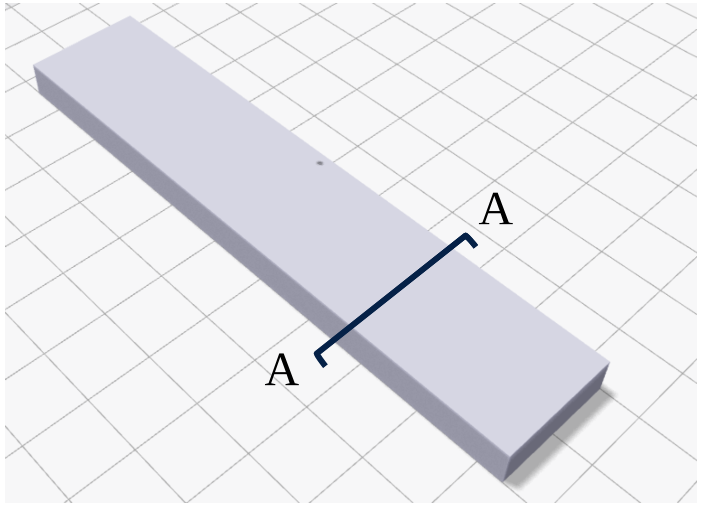
Talc powder compaction
Wabash hot press

Mold heating
Carbolite Laboratory Convection Oven

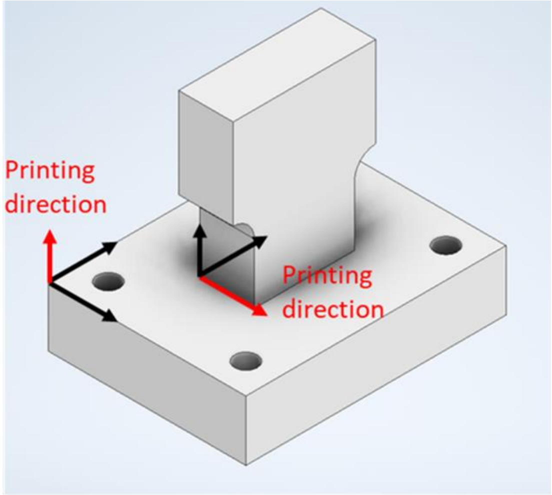
FF3D: FDM Test Samples

- Flexure coupon: 20 x 100 x 6 mm with LCF and SCF printed on MarkForged
- T-bracket with a dovetail join: two-piece assembly SCF printed on DM
- Automobile pedal: Single piece 260 mm long SCF printed on MarkForged

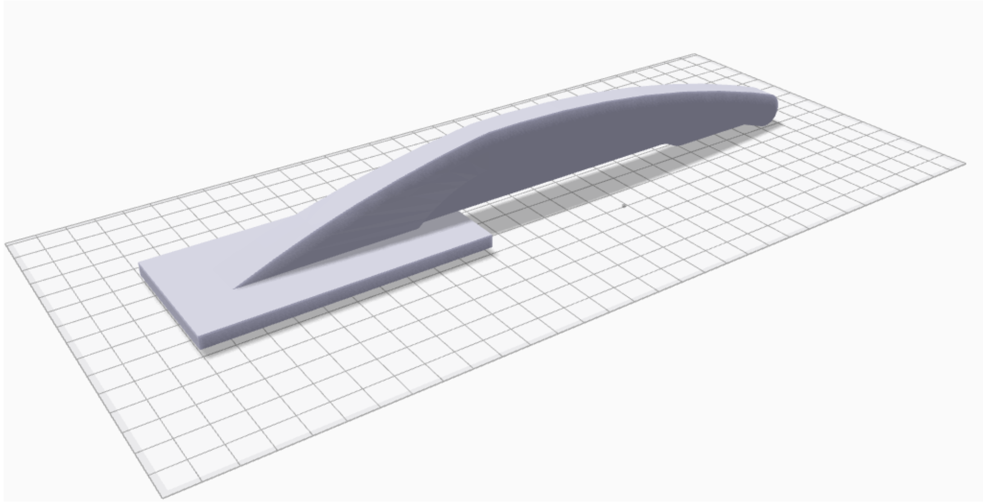




Flexure coupon



T-bracket

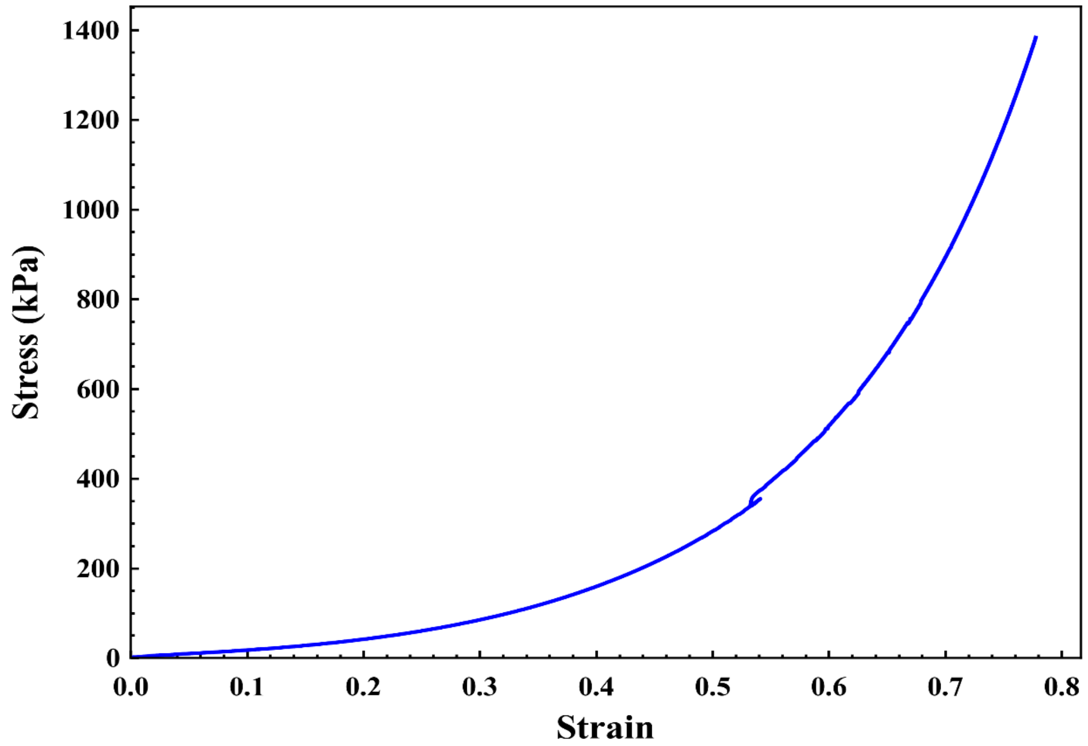


Automobile pedal

FF3D: Talc powder compaction

COMPOSITES MODELING AND MANUFACTURING LAB

- Mold01: 5 x 5 x 1 in mold was used for compaction test.
- With talc bed 0.2MPa (**20 psi**) to 1.3MPa (**180 psi**) isostatic compaction can be applied

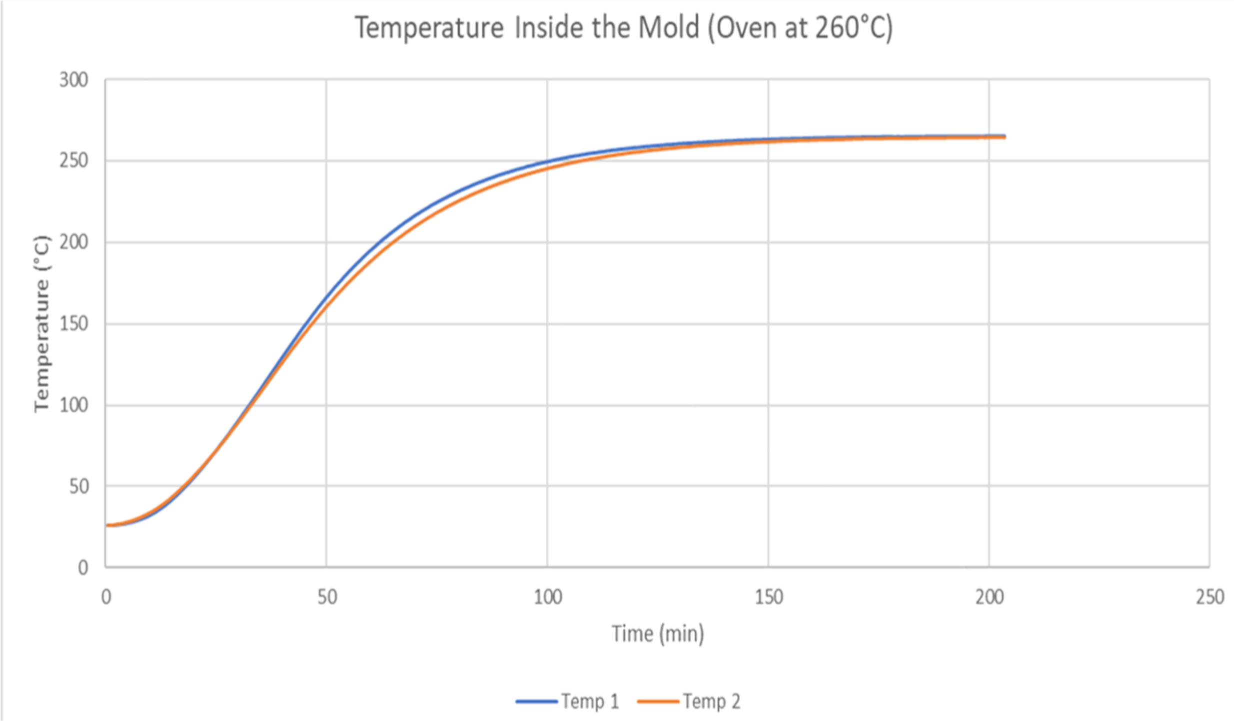


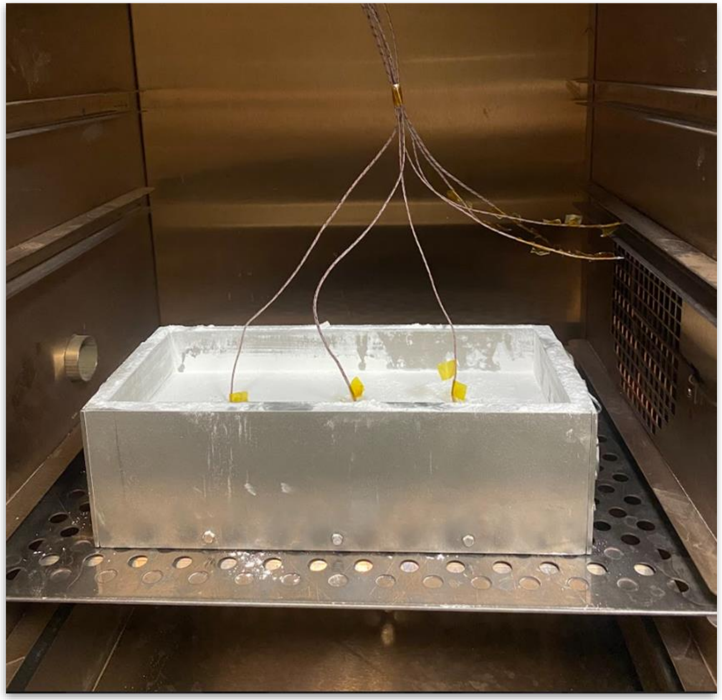
Mold01: Talc bed under compression

FF3D: Mold heating

- A temperature gradient from 50°C to 260°C observed across the compressed ~1.5-inch-thick talc medium.

- The temperature reaches 260°C within a 2-hour.

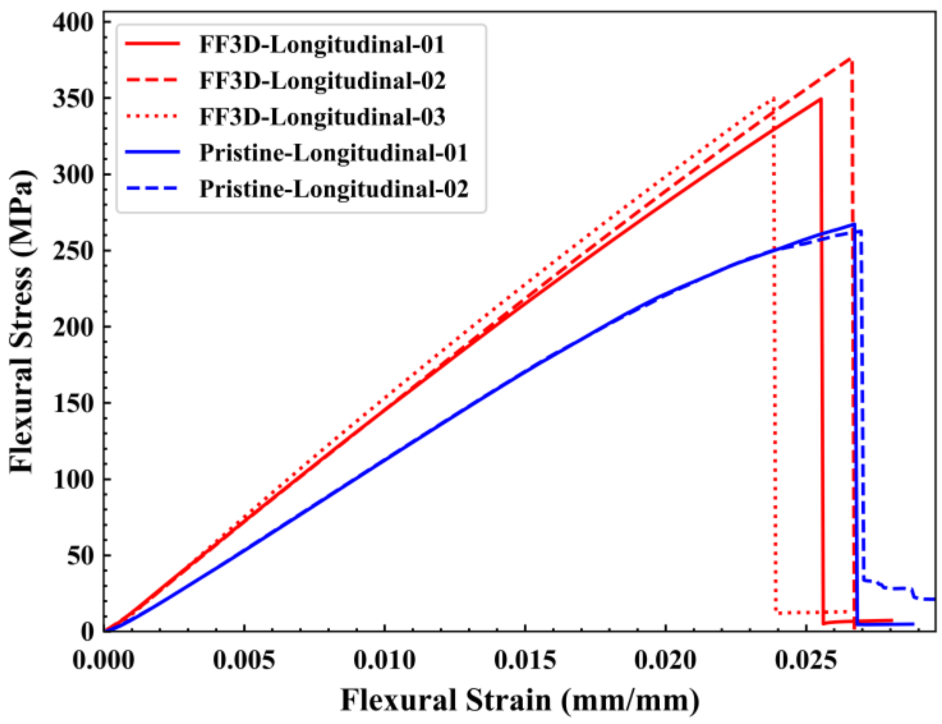


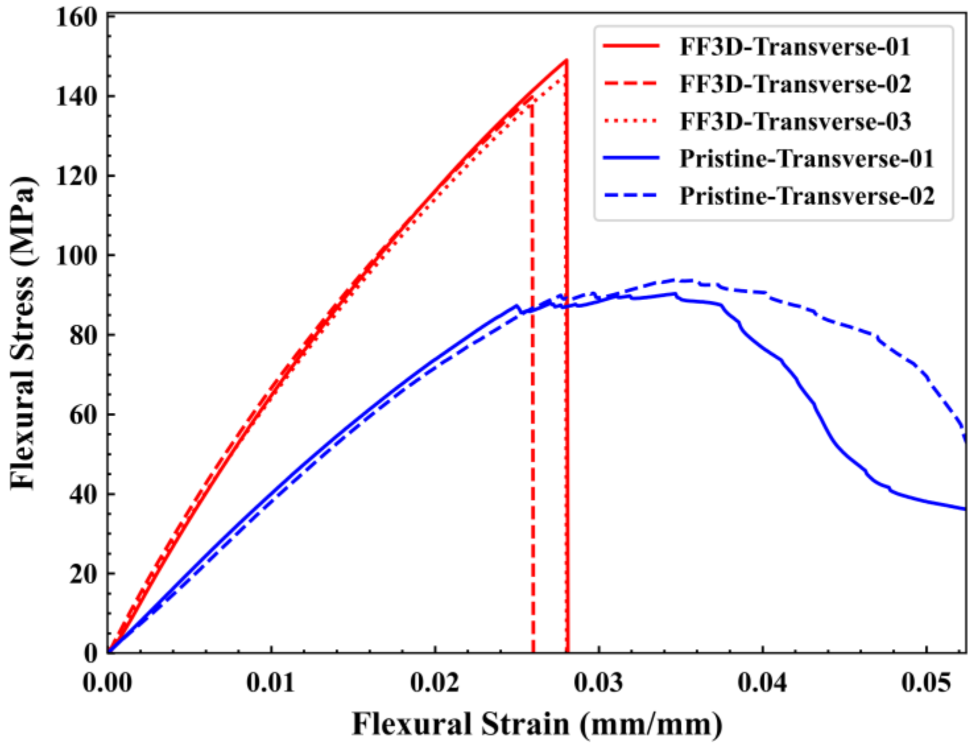


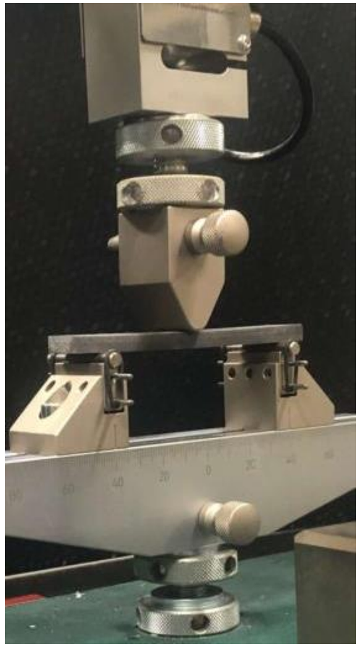
Mold02: Talc bed with thermocouple

Flexure coupon

- Longitudinal coupons exhibit a 25% increase in flexural modulus and a 40% increase in flexural strength, while transverse coupons show a remarkable 65% increase in flexural modulus and an impressive 66% increase in flexural strength.



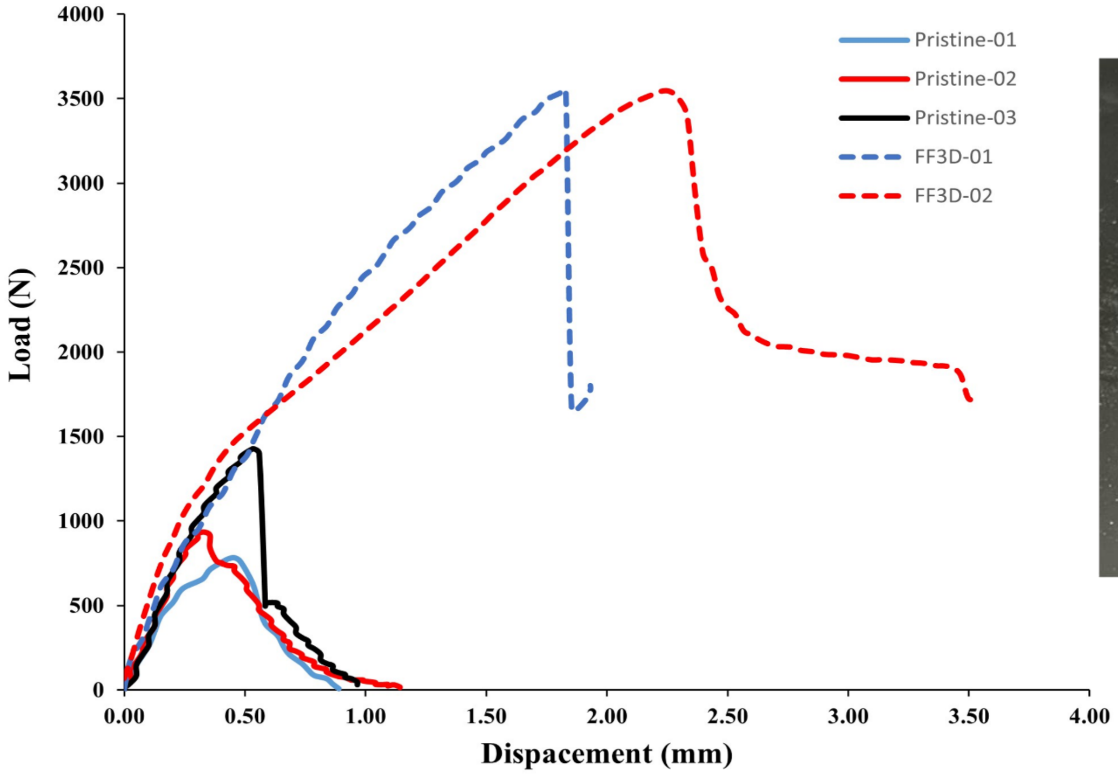


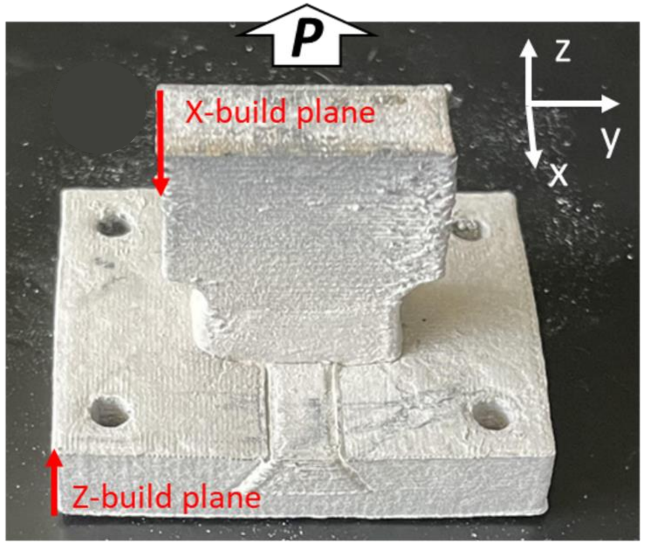


Experimental Setup

T-bracket

- In the T-bracket assembly, a notable 130% of the expected breaking strength was achieved.
- The assembly failure occurred at the dovetail joint due to insufficient fusion.



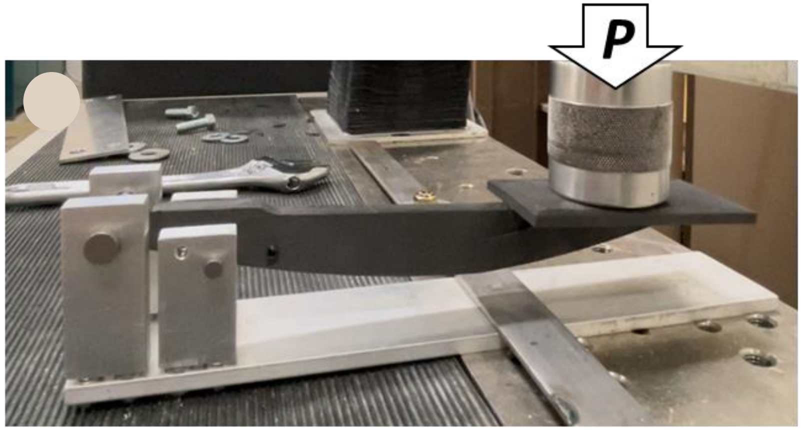


T-bracket after FF3D

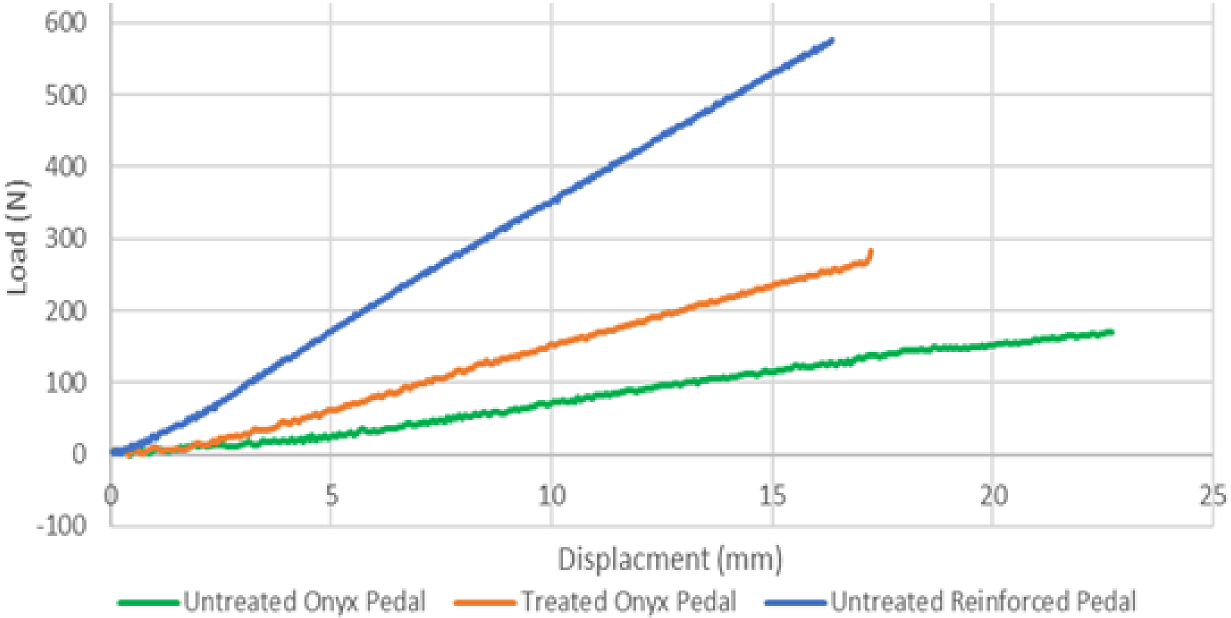
T-bracket Failure

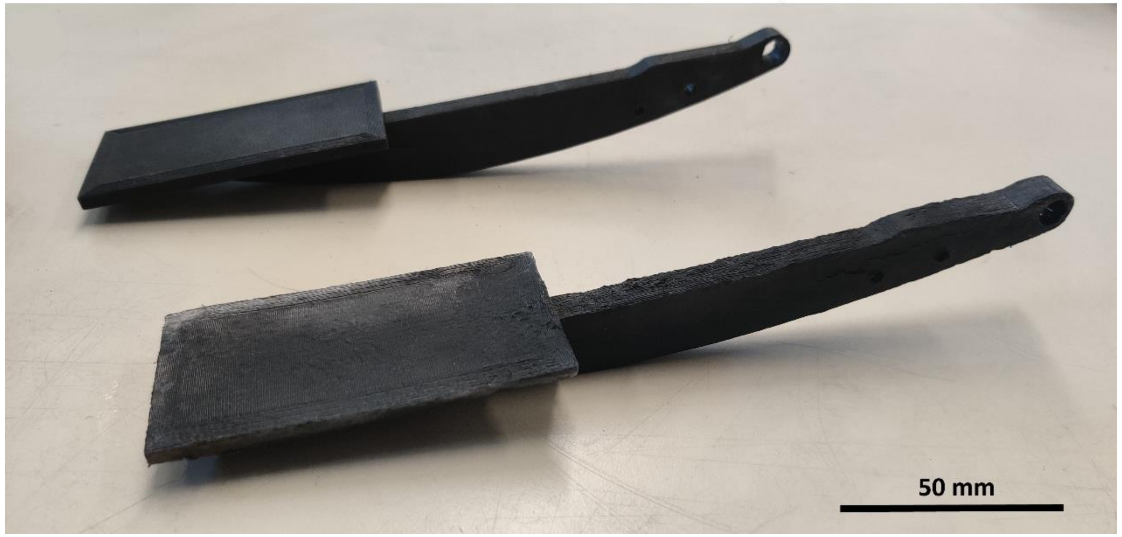
Automobile pedal

- After FF3D, an increase of 105% in the modulus is observed in samples with SCF (only Onyx), tested before reaching failure.
- By reinforcing with LCF, the stiffness of the pedal increases to four times that of SCF.



Experimental setup

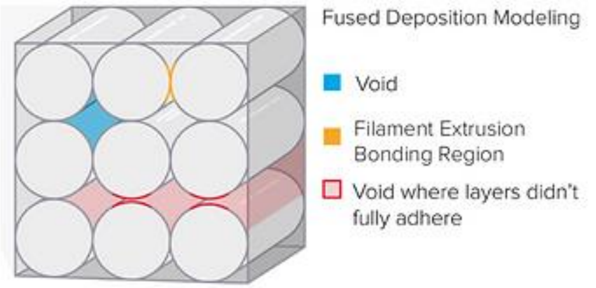


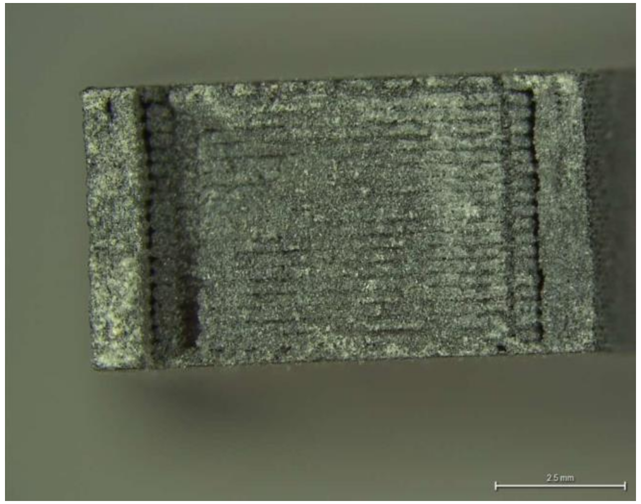


Automobile pedal before and after FF3D (and sandblasting)

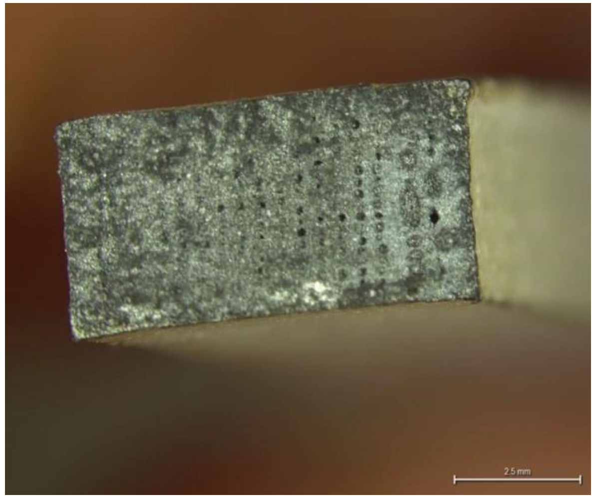
Macroscopy Results of FF3D

- In pristine FDM samples, large inter-layer voids & inadequate adherence were observed.
- Heated mold without compaction resulted in improved layer adherence.
- When the mold was heated with compaction, the presence of voids reduced to less than 1%.





FDM



Mold heating w/o compaction

Mold heating with compaction

Conclusions

- The FF3D process transforms FDM from quasi-2.5D to true 3D fabrication, offering versatile and effective composite parts with optimized fiber orientation.
- Post-fabrication fusion compaction improves stiffness through increased crystallinity and eliminates inadequate fusion bonding and thermal residual stresses.
- Complex geometries and topology-optimized elements become achievable with this approach.
- The process significantly reduces voids (<1%), meeting high-performance composite requirements.
- FF3D addresses traditional FDM limitations, enabling the fabrication of high-performance, fully 3D components with tailored fiber orientation.