Enhancement of Mechanical Strength and Structural Optimization in 3D-Printed Neutron Shielding Structures

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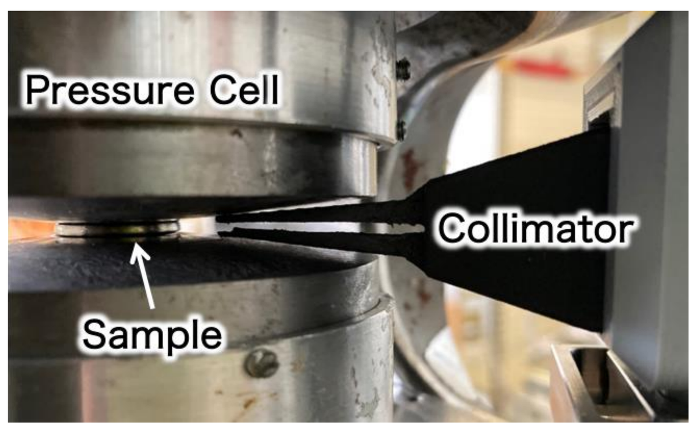
Introduction

Neutron probes are widely used in materials science and fundamental physics research. Reducing background noise through neutron shielding and optical components is essential for improving experimental precision.

PSI has developed a 3D-printed shielding material by adding B_4C to its proprietary Poly Lactic Acid(PLA), PSI-PLA. However, PLA exhibits a characteristic where the addition of B_4C leads to a decrease in mechanical strength. **This research aims to improve the mechanical strength of B_4C-added PLA through the addition of reinforcing materials and heat treatment.**



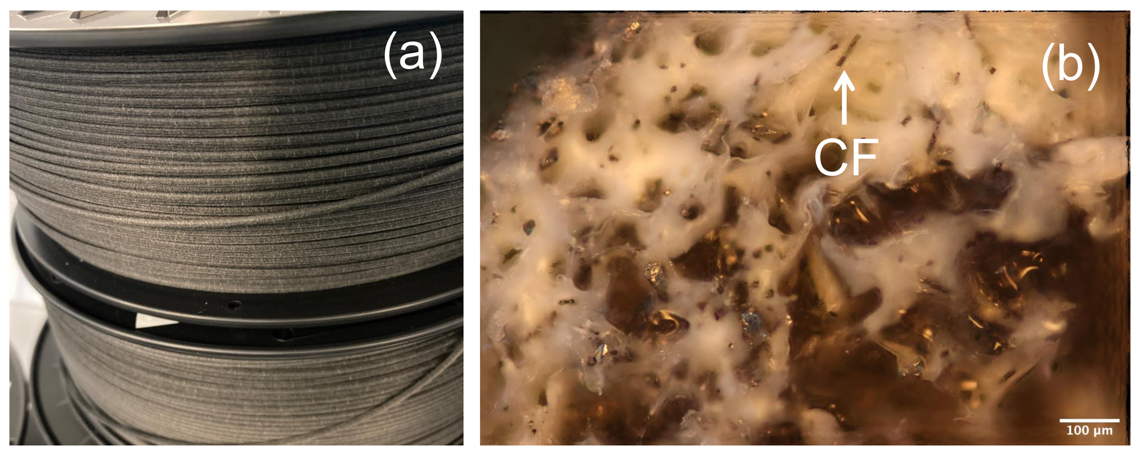
Collimator with fine structure near the sample (3D-Printed Neutron Shielding Structures)

Material lists
PSI-PLA 100%
PSI-PLA 75% + B_4C 25 %
PSI-PLA 95% + CF 5 %
PSI-PLA 75% + B_4C 20 % + CF 5 %
Commercial PLA 100 % for PLA-A, PLA-B, PLA-C
Commercial PLA-C+CF (PLA 92-96 % + CF 4-8 %)

Filament Development

This study adds Carbon Fiber (CF) reinforcement to PLA+B_4C to enhance mechanical properties by counteracting the embrittlement of PLA caused by B_4C. CF possesses three times the tensile strength of glass fiber. When added to plastics, it enables load transfer through the resin to each fiber, resulting in mechanical strength exceeding that of individual fibers.

The PSI Optics Group has established facilities for filament development. As an initial step, **we developed filaments at PSI by adding 5% carbon fiber to both PSI-PLA and PSI-PLA+B_4C.**



(a) Developed PLA-PSI+B_4C+CF filament, (b) Cross-section of the filament shown in the left figure

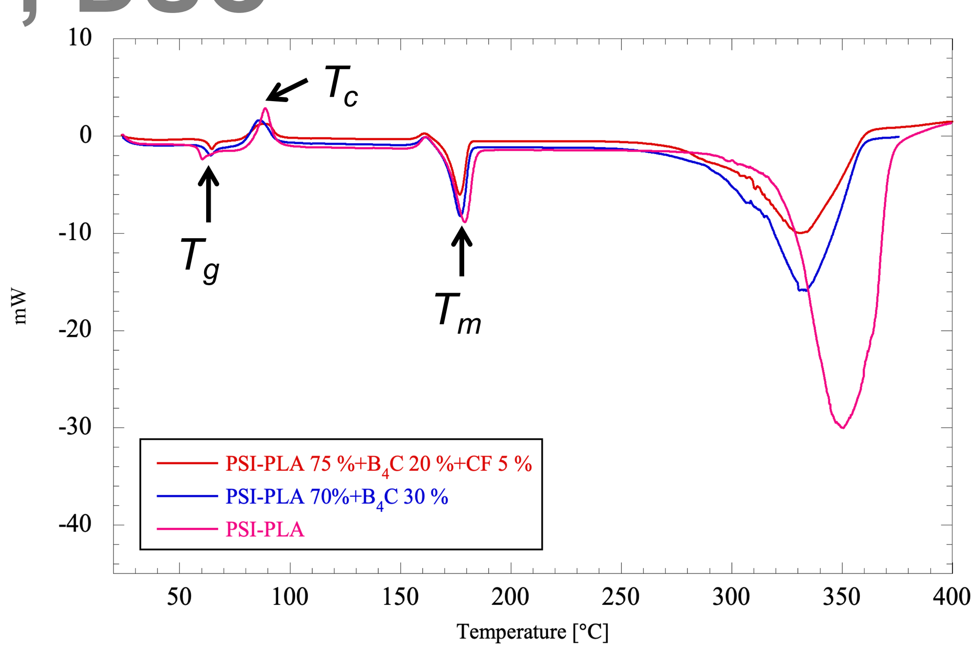
Carbon fiber properties	
Length	100 ± 20 μm
Diameter	7 ± 2μm
Tensile strength	3500 MPa

Differential Scanning Calorimetry; DSC

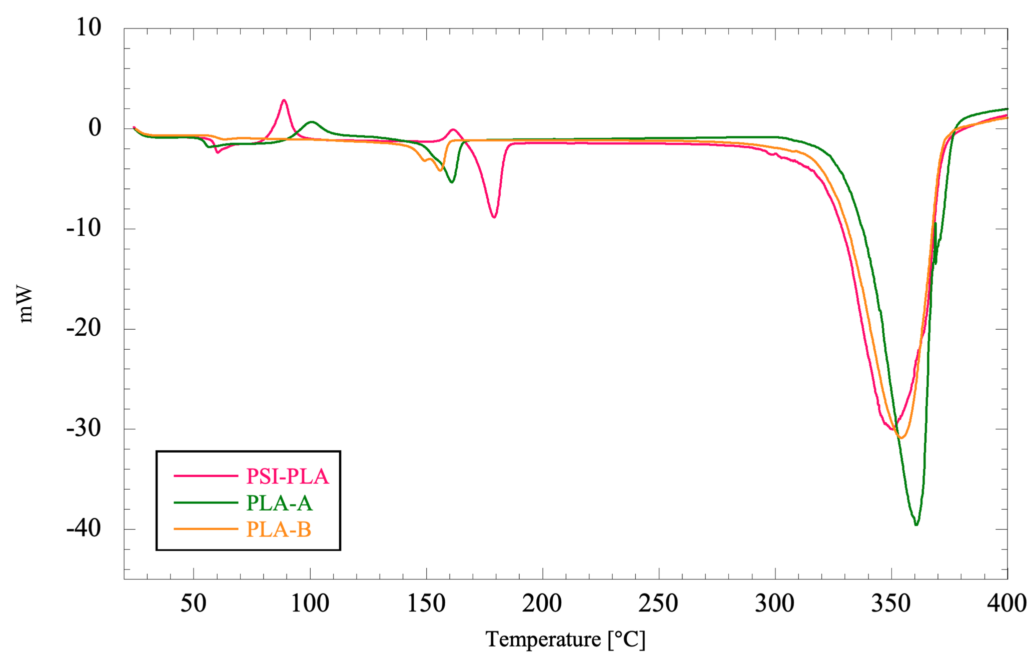
Understanding the thermal properties of materials is crucial in heat treatment. PLA, a crystalline plastic, can become unstable and amorphous after 3D printing. Post-print heat treatment, specifically annealing, can cause it to crystallize.

Using DSC, we measured the glass transition temperature (T_g), crystallization temperature (T_c), and melting temperature (T_m).

As a result, **it was found that changes in the type of PLA had a greater influence than the effect of the mixture on thermal properties.**



Measurements using the same PLA showed that thermal properties did not change significantly regardless of the mixture.

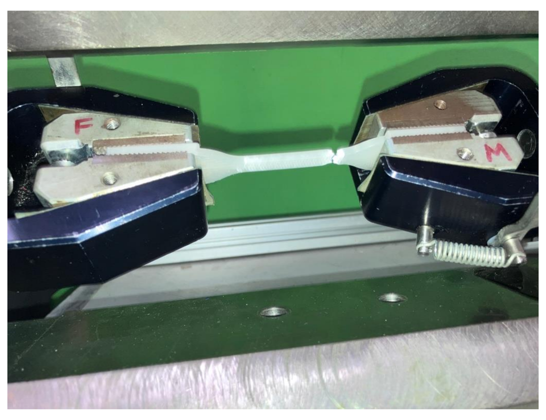


Changing the type of PLA changed T_g, T_c and T_m.

Tensile Test (Pre-Test)

Instruments	
The POLDI load frame	Mono-axial Tensile Testing Machine
Load capacity	Maximum 10 kN for flat test-piece
Speed	0.05 mm/s

Test piece	
Standard	ASTM D638-14: Type IV
Cross-section	Width 6 ± 0.5 mm × Thickness 3.2 ± 0.4 mm
Number	2 per condition



PSI-PLA fracture

Results

Materials	Ultimate tensile stress [MPa] w/o annealing	w/ annealing	Ratio
PLA-C	51.3	55.1	1.07
PLA-C+CF	49.7	55.6	1.12
PSI-PLA 100%	48.0	45.3	0.94
PSI-PLA 75% + B_4C 25 %	45.1	49.4	1.10
PSI-PLA 95% + CF 5 %	26.0	22.8	0.88
PSI-PLA 75% + B_4C 20 % + CF 5 %	21.1	19.9	0.94

*When all specimens are deemed invalid at break, reference values are shown in gray.

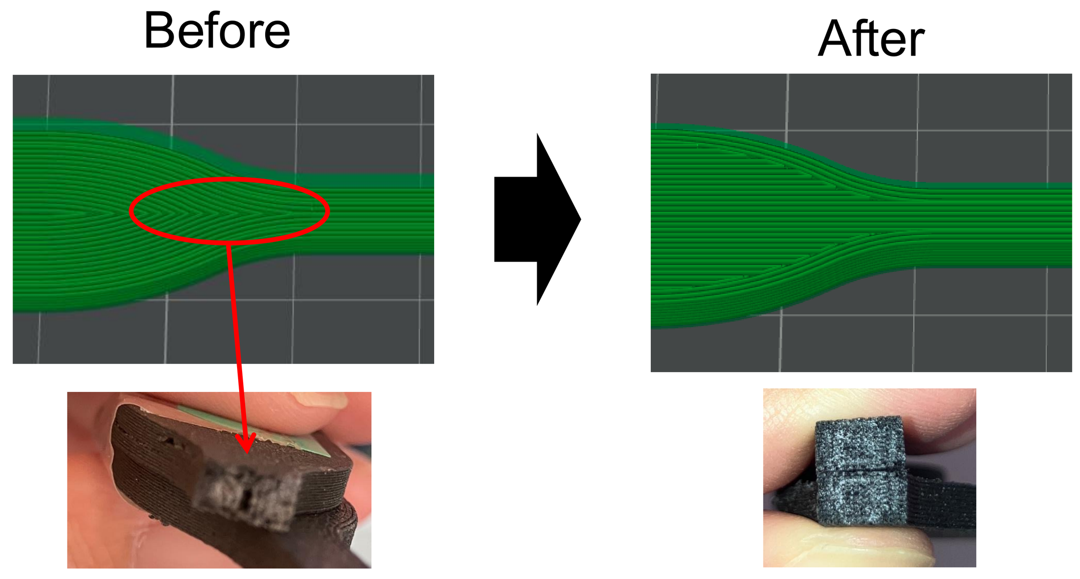
- It was found that PLA with B_4C added has about half the mechanical strength. Strength enhancement is crucial.
- Commercial PLA-C showed strength improvement through annealing, but no strength improvement was observed with CF. Further investigation of the filament composition is necessary.
- Adding CF of PSI-PLA shows no mechanical strength improvement. Whether this is due to the amount or length of CF added, or insufficient optimization of annealing and print settings, will be investigated in the future.

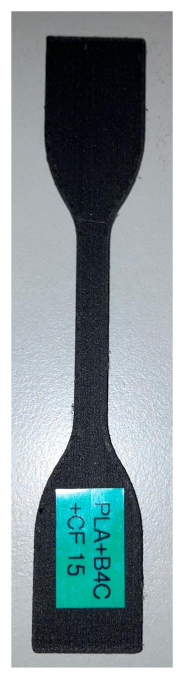
The pre-test did not meet sufficient conditions regarding tensile speed, number of test specimens, and deflection of the gripping section; therefore, the test method will be improved going forward. The distribution of B_4C and CF, and the investigation of voids formed within the filament due to mixing will also be studied in the future.

Preparation 1: Printing

An attempt was made to optimize the 3D printing settings and structures. A structure without large voids that would become invalid during tensile testing was achieved, but non-destructive testing is required for the internal areas.

Before After





Structural Settings and Fracture Surfaces in 3D Printers

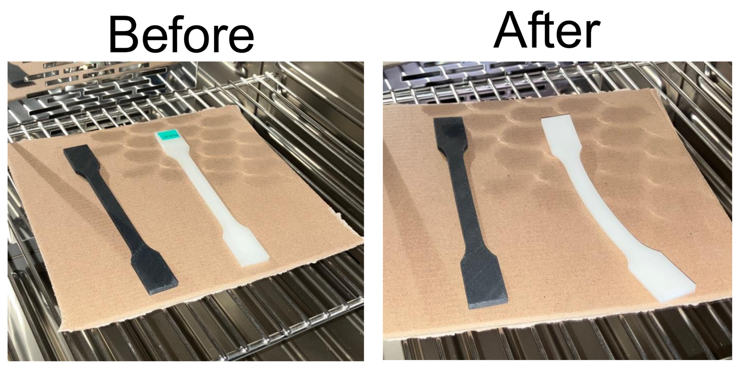
Preparation 2: Annealing

It is known that crystalline plastics like PLA can be encouraged to crystallize by annealing between their T_g and T_m.

Annealing at 110 ℃ for 1 hour caused significant warping in PLA, whereas adding B_4C+CF suppressed this warping.

To further suppress warping, the material was pressed between plates and heated at 80 ℃ for half day. This revealed expansion in the layered direction and shrinkage parallel to it.

Before After



PLA and PLA+B_4C+CF annealed at 110 ℃ for 1 hour

Annealed at 80 ℃ for half day

Materials		Fracture site [mm] before	after	Ratio
PSI-PLA	width	6.03	5.98	0.99
	height	3.50	3.59	1.03
PSI-PLA + B_4C + CF	width	6.03	6.01	1.00
	height	3.41	3.41	1.00