Enhancing PLA Strength: Exploring the Power of Salt Remelting

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Abstract

- The study investigates a common weakness in FDM 3D printed parts, particularly their weakness in the z-direction, which is due to insufficient bonding between layers due to low temperatures. This project evaluates the effectiveness of a new method to mitigate z axis weakness known as salt remelting, where 3D printed parts are packed into a container of melted salt and are heat up right past the melting temperature of the material. The results revealed that the parts salt remelted in the oven to an internal temperature of 180 ± 0.25°C achieved a tensile strength of 58 ± 2 MPa in the Z direction, equal to the tensile strength of a sample being broken in the XY direction (60 ± 7 MPa), however had significant thickness compared to the non remelted control samples (105 ± 2%).

Introduction

- The explosion of FDM 3D printing in the past decade has allowed people to make plastic parts for cheap.
- However, there is one major drawback of FDM Printing, which is z axis strength.
- So, we explored two different annealing methods to try to improve Z axis strength, annealing and salt remelting.

Figure 1: The mass production of 3D printers such as this Ender 3 have brought FDM 3D Printing more into the mainstream. This particular model can be found as low as $90

Figure 2: Chemistry Furnace Used to Anneal & Remelt samples.

Methods and Materials

- Breaker bridge
  - Uses load cell
- 3d printer

[1]

Infill Density [%]	Layer Thickness [mm]	Bed Temperature [°C]	Nozzle Temperature [°C]	Glass Transition Temp [°C]	Print flow rate [mm^3/s]
100	0.2	55	240	60-65	6

- Calculation of tensile strength
  - $\sigma = F/A$
  - Where σ is tensile stress
  - F is Force
  - A is Cross sectional area normal to the force axis.
- Deflection Measurement
  - Calipers and micrometer

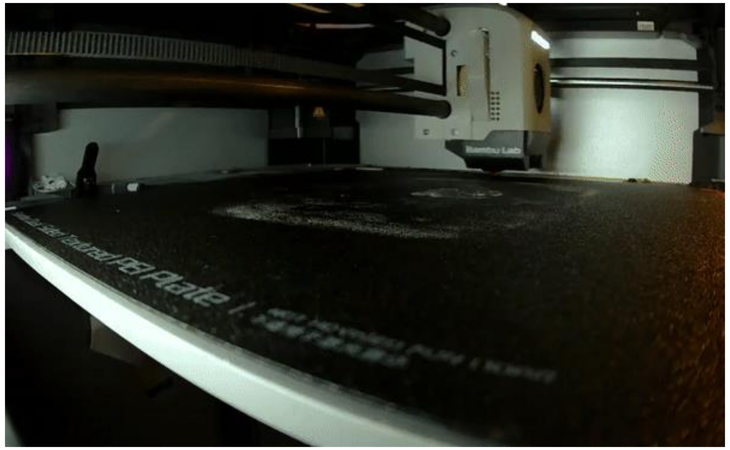

Figure 3: Gif of 3D printer creating parts

Annealing Methods

- Oven Annealing
  - Evaluate the impact of temperature on strength
  - Objects placed in chemistry furnace preheated to 70 °C, 90 °C, 110 °C for 1 hour
- Salt Annealing
  - Printed parts placed into a container of salt and remelted in a chemistry furnace until an internal temperature of 140 & 180C as measured by a food thermometer.
  - Finer grain salt, for dimensional accuracy
  - 140 °C, and 180 °C

Figure 4: Salt annealing process.

Figure 5: dog-bone 3D printed shape to adhere to the breaker bridge.

Load cell

- Uses a strain gauge that can measure small changes in resistance (R)
- $R = \frac{\rho}{A} L$
  - ρ is the resistivity of the wire
  - A is the cross-sectional area of the wire,
  - L is the total length of the wire.
- The small change in resistance is converted to a change in voltage using a Wheatstone bridge and an op-amp.
- $e_0 = \left(\frac{-V_b R_1 R_{SG,0}}{R_1 + R_{SG,0}} * F \right) * \varepsilon_a$
  - e_0 is the voltage difference
  - V_b is the input voltage
  - $R_{SG,0}$ is the resistance of the strain gauge at rest
  - ε_a is the strain.

Tensile Tester

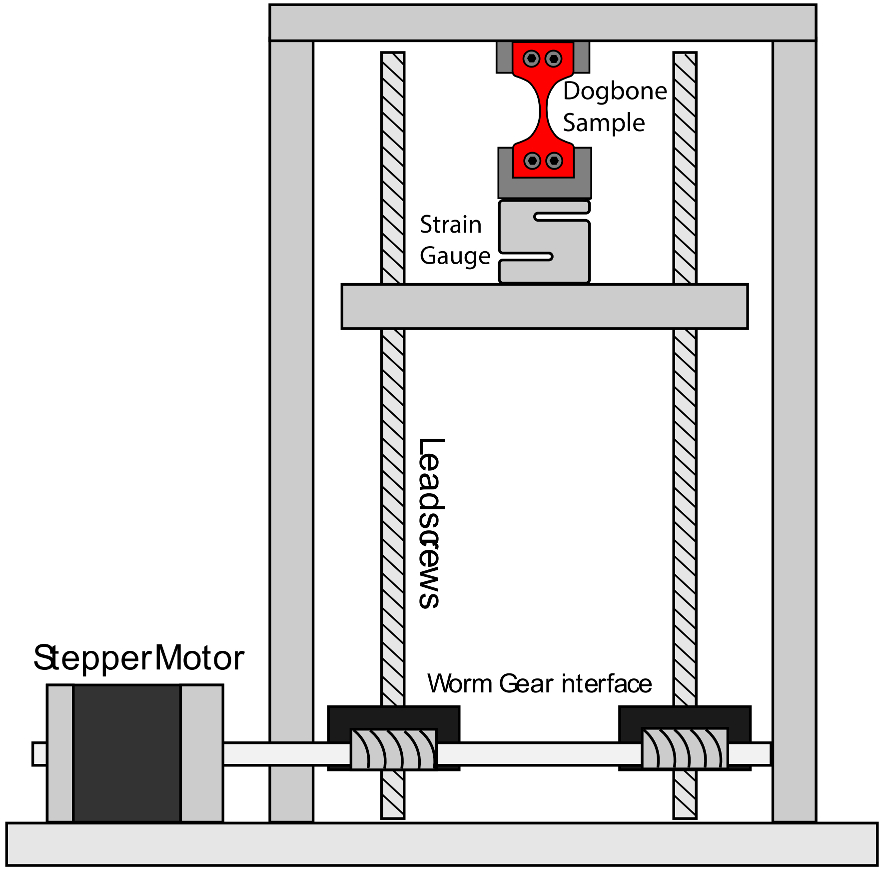

Figure 6: Breaker bridge setup.

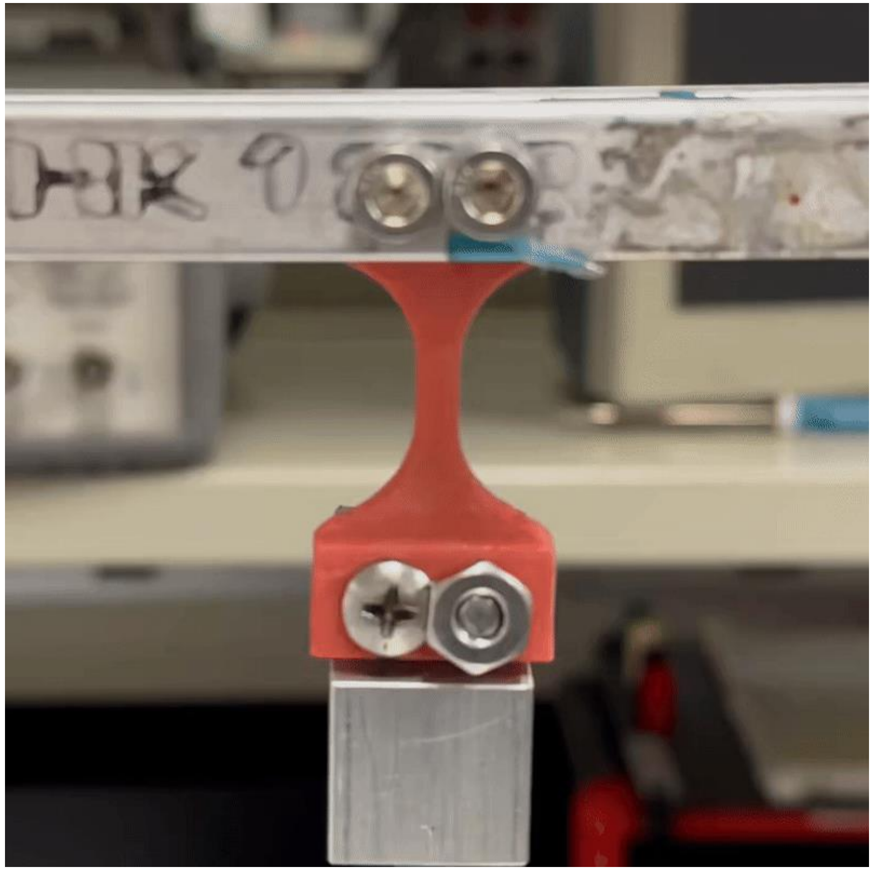

Figure 7: Video of 180 °C salt annealed tensile sample on breaker bridge.

Results

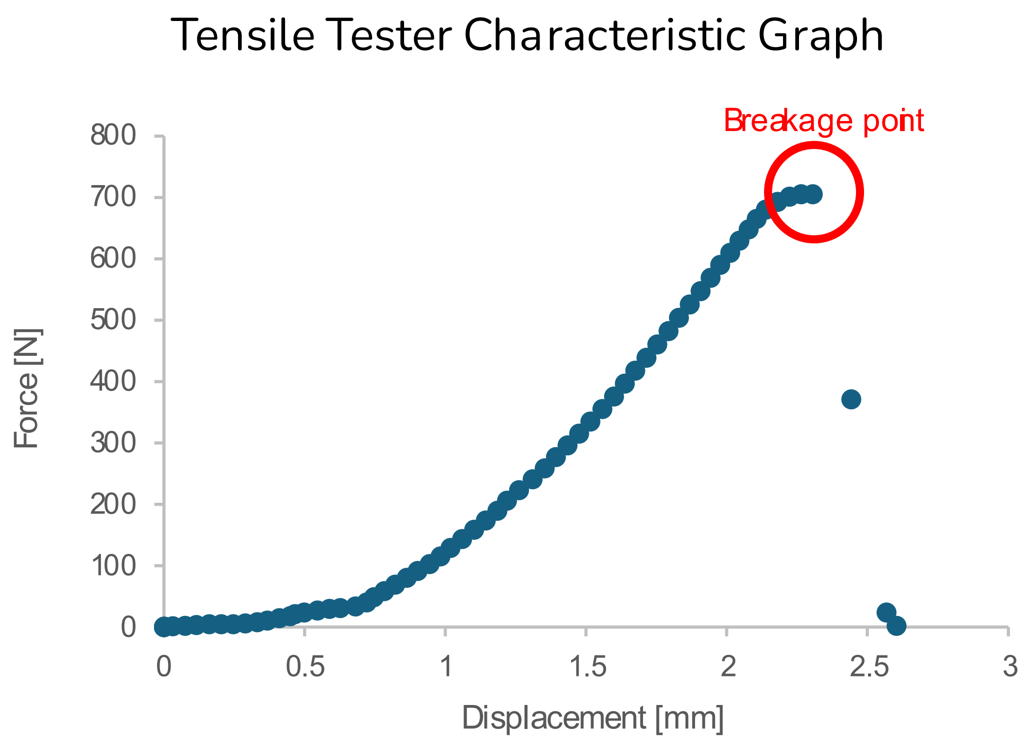

Figure 8: Visualization of max force on tensile sample.

- Arbitrary plot – 180 °C salt annealing
- Force was calculated
  - Mass x 9.81 [m/s^2]

- Characterization plot is outputted from the breaker bridge setup
- Breakage point = max force
- Calculate stress

Results: Tensile Strength

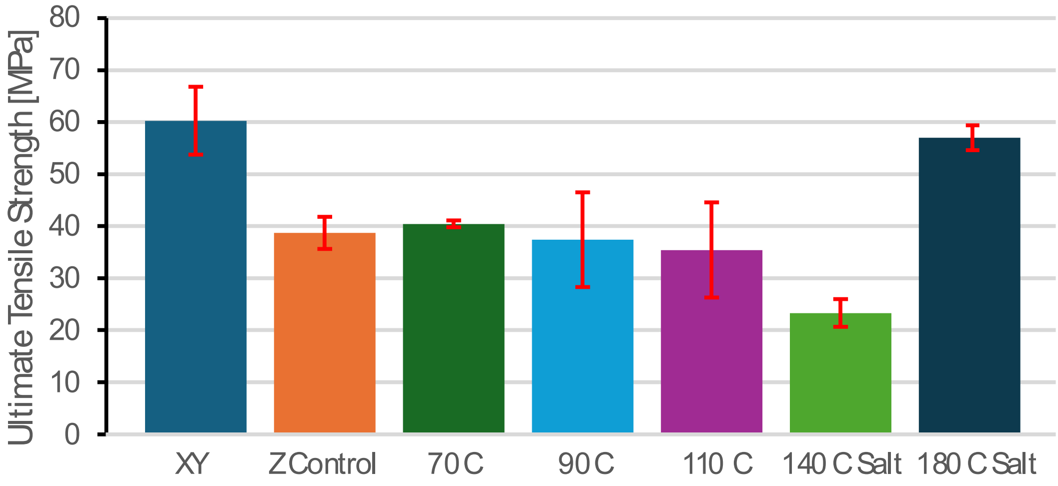

Figure 9: Ultimate Tensile Strength of each sample at each temperature including salt annealing method.

- $\sigma = F/A$
- Higher temperature causes molecular structure to break down up to certain point
- Melting temp of PLA is ≈ 175 °C [2]

Examination of Breakage

PLA fracture test printed horizontally. Stress marks were formed, and piece broke in an irregular fashion.

Figure 10: Breakage of horizontally printed sample.

PLA fracture test, oven annealing with no salt. Part broke right along the layer line.

Figure 11: Although oven annealed, the layer lines didn't fuse together.

PLA fracture test, heavy annealed salt at 180 °C, part melted together, and layer lines eliminated.

Figure 12: Past the melting point of PLA. Uniform break with no layer lines.

Results: Dimensional Analysis

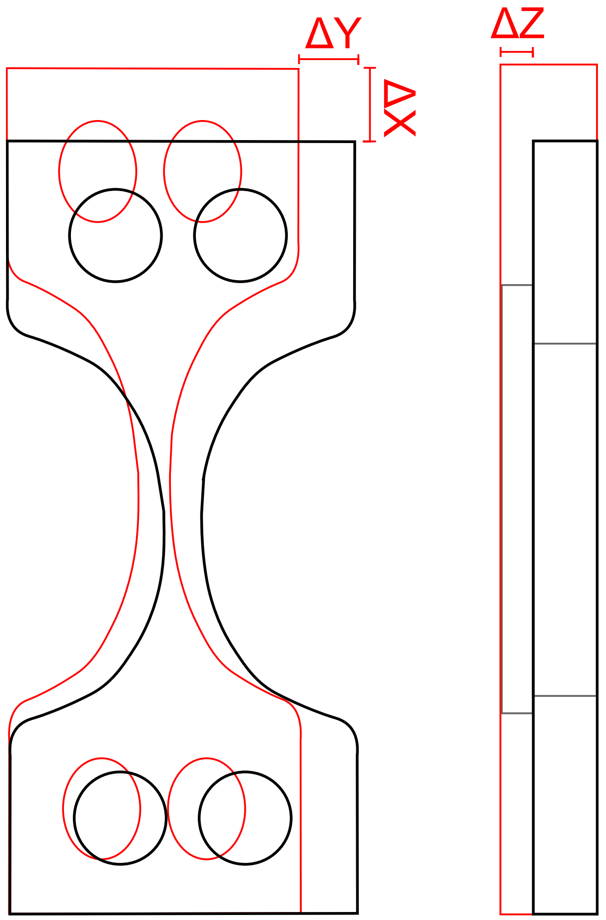

Figure 13: dog-bone deflection in dimensional analysis.

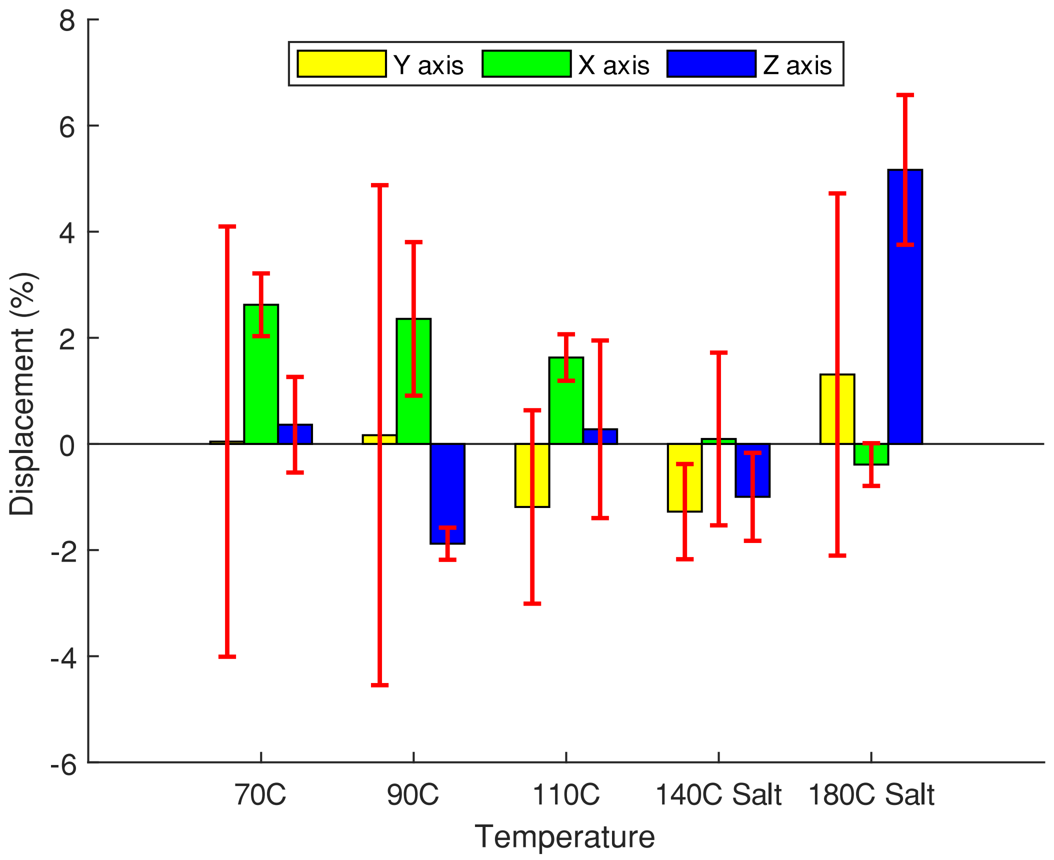

Figure 14: Displacement after annealing at different temperatures

Discussion

- Cavities on the backside of salt annealed parts at 180 °C
  - Uneven annealing, leads to areas of reduced structural integrity
  - Air gaps within the print

- Warping on annealed parts
  - Uneven cooling, residual stresses, placement on the print bed, material shrinkage

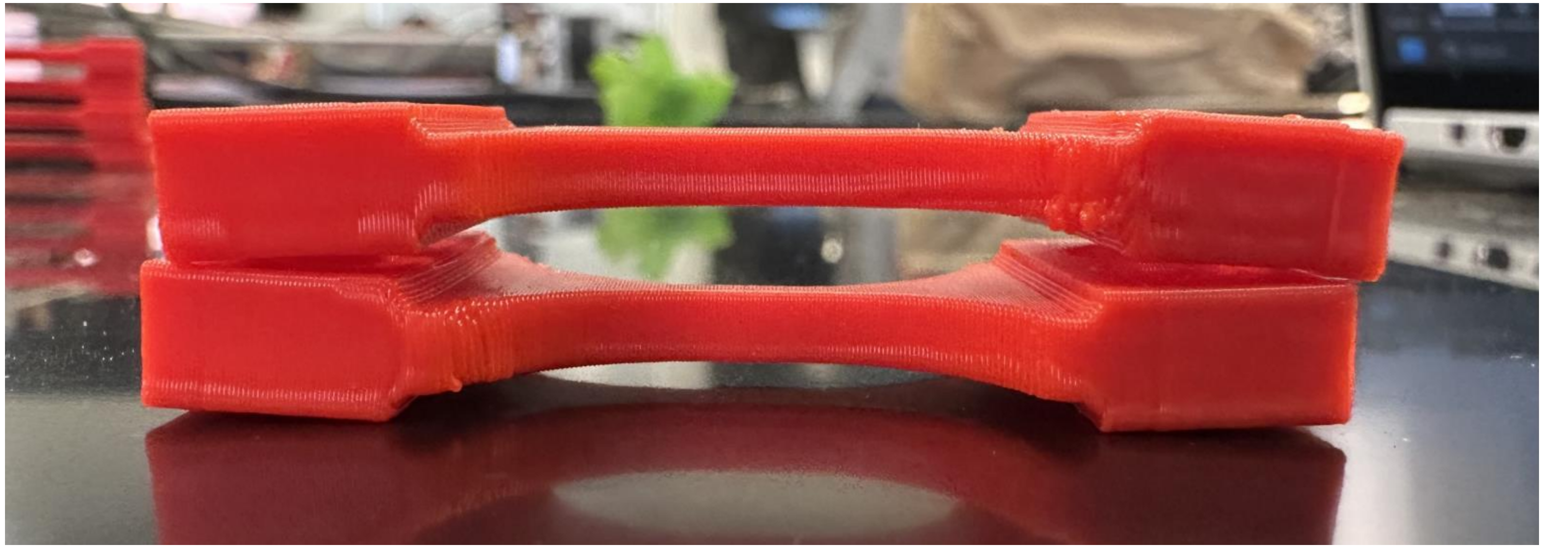

Figure 15: Warped 110C 3D printed samples

Figure 16: 180 °C salt annealed sample with cavities. Air pockets that popped as the sample was melted

Conclusion/Real World application & Limitations

- While we may have had some pitfalls (literally) with the fully salt remelted samples, that issue can be mitigated by manually changing the extruder flow rate percentage to a slightly higher value.
- Furthermore, the rough surface texture of the part can be smoothened by using a smaller grain of salt
- This process can be used to make isotropic FDM 3D Prints without significant deflection or displacement
- The parts must be 100% infill or else

Figure 17: Example of 80% infill. Source: CNC Kitchen on YouTube

Equations

- Uncertainty calculation
  - $\sigma = \sqrt{\frac{\sum(x-\bar{x})^2}{n-1}}$
  - $t_{estimator} = 2.571$
- Force equation
  - $F = mg$
- Tensile strength
  - $\sigma = F/A$

Sources

[1] KARTAL, F., & KAPTAN, A. (2023). Effects of annealing temperature and duration on mechanical properties of PLA plastics produced by 3D printing. *European Mechanical Science*, *7*(3), 152–159. https://doi.org/10.26701/ems.1290961

[2] Franta. (2018, January 1). Prusament Pla. Prusament. https://prusament.com/materials/pla/#:~:text=PLA%20melts%20at%20a%20relatively,breaks%2C%20it%20likes%20to%20shatter.

[3] Hermann, S. (2020, October 24). Testing the strength of 3D prints re-melted in salt. CNC Kitchen. https://www.cnckitchen.com/blog/testing-the-strength-of-3d-prints-re-melted-in-salt