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Annealing Guide for PEN 3D-Printed Parts

Product: FLXR Engineering PEN Natural & PEN HF

1. Purpose

Annealing is a post-processing step that improves the thermal, mechanical, and hydrolysis resistance of 3D-printed PEN (*Polyethylene Naphthalate*) parts.
It is strongly recommended for parts exposed to repeated autoclaving, prolonged heat, or high-humidity environments.

Benefits for PEN Natural

- **Heat deflection temp. (HDT, 0.45 MPa):** increases from **116 °C** to **166 °C**
- **Tensile strength**: improves by 5–10%
- **Long-term hydrolysis resistance**: improves by ~25% at 80 °C (100% RH)

Benefits for PEN-HF

- **Heat deflection temp. (HDT, 0.45 MPa):** increases from **108 °C to 161 °C**
- **Tensile strength**: improves by 5–10%
- **Long-term hydrolysis resistance**: improves by ~20% at 80 °C (100% RH)
- *Crystallizes approx. 15% faster, shorter annealing hold times*

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2. General Safety and Preparation

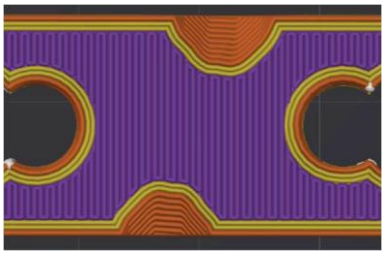
- **PPE**: heat-resistant gloves, safety glasses
- **Oven**: temperature control, hot circulated dry air
- **Handling**: allow slow cooling to avoid internal stress
- **Placement**: use a tray to contain quartz sand bath. Use >400 grit to avoid imprinting sand texture on the surface with pressure

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3. Slicer Recommendations

To improve dimensional stability and reduce warping during annealing, use design and slicing settings that minimize internal stress. We recommend the following practices:

1. Avoid long, straight lines – Long, continuous paths tend to warp or distort.
2. Segment the path into shorter lines – Use infill that break up long spans.
3. Prefer a 30° orientation to the short side – Setting infill at 30° relative to the shorter dimension keeps the part shape.
4. Use rectilinear infill – Alternating patterns relieve internal stress more uniformly during annealing.
5. Apply 100% infill whenever possible – Fully dense parts anneal more predictably, avoiding potential void expansion.



Orient the slicer on the short path if possible

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4. Annealing Methods

Method 1 – Direct Oven Annealing

Best for: Simple, uniform shapes such as cubes and cylinders, and where dimensional accuracy is not critical.

Procedure *(based on a part size of 20 mm × 20 mm × 20 mm)*:

1. Place the part in an oven and set the temperature to **165 °C**.
2. Hold at 165 °C for **17 minutes**.
3. Turn off oven and allow slow cooling inside to **100 °C** (20–25 minutes) before removal.

Expected dimensional changes:

- **XY shrinkage**: ~10%
- **Z growth**: ~7%

Method 2 – Sand Bath Annealing (Medical/dental quartz sand recommended)

Best for: Parts requiring tight dimensional control and complex geometries. Use >400 grit quartz sand for smoother surface. 120 grit could imprint a slight texture onto the part.

Procedure:

1. Spread **5–7 mm** of **loose** quartz sand in a metal or borosilicate glass container.



2. Add a 1 cm layer of quartz sand and compact it to form a level bed. Place the parts on the bed, then cover them completely with loose sand. Gently tap the container to distribute and then compact the sand evenly with another 1 cm on top.





3. Heat oven to **180 °C** and hold for **30 minutes**.
4. Turn off the over and allow to slowly cool to **100 °C** (35-45 minutes) before taking out the parts buried in sand or quartz bath.




Expected dimensional changes:

- **XY shrinkage**: <5%
- **Z growth**: <3%

Notes for PEN-HF

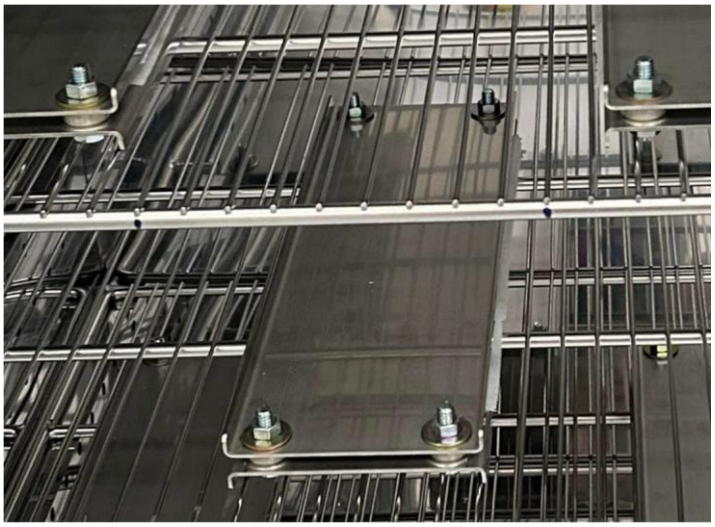
- Reduce hold times by 10-15% for both methods 1 or 2.
- Dimensional changes are similar.

Method 3 – Between Two Steel Plates (SUS304 or SUS316)

Best for: Parts with two flat surfaces requiring tight dimensional control.

Procedure:

1. Prepare two flat stainless steel plates. Ensure both surfaces are clean and free of debris.
2. Place the printed part between the two plates. Use spacers (nuts with washers) at the corners to control the gap. The spacer height should match the part height to avoid compressive deformation.



3. Secure the assembly so that the plates are held parallel with uniform contact. Place the assembly in an oven and heat to **185 °C**. Hold for **22 minutes**.
4. 4. Turn off the over and allow to slowly cool to **100 °C** (25-35 minutes) before removing the part.

Expected dimensional changes:

- **XY shrinkage**: <5%
- **Z growth**: <3%

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4. Troubleshooting and Tips

High aspect ratio parts

- For tall, thin, or long parts, **pre-design for shrinkage** in the slicer to compensate for annealing changes.
- Apply an XY scale-up and Z scale-down of the 3D model in slicer based on the method's expected changes.

Preventing sand texture imprinting to part

- Only use **loose** sand in the sand bath method — never compact.
- Compacted sand may cause grains to imprint a texture onto the part surface. Unless intentional texture is desired.

Recognizing crystallization state

- Under-crystallized parts can be annealed again without damaging the part.
- Increase the holding time to achieve desired results.
- Based on XRD analysis, methods 1, 2, and 3 achieved a crystallinity of 50~65%
- Finished parts are **uniform opaque white**.

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5. Dimensional Change Reference Table

Method	Material	XY Shrinkage	Z Growth	Hold Temp	Hold Time*
Direct Oven	PEN Natural	~10%	~7%	165 °C	20 min
Sand Bath		<5%	<3%	175°C	30 min
SUS Plate		<5%	<3%	185 °C	22 min
Direct Oven	PEN HF	~10%	~7%	165 °C	17 min
Sand Bath		<5%	<3%	175°C	25 min
SUS Plate		<5%	<3%	185 °C	19 min

**Times are based on a part size of 60 mm × 10 mm × 10 mm. Adjust for larger or smaller parts.*

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6. Cooling and Handling

- Allow parts to cool **inside the oven or sand bath** until they reach 100 °C before removal. Crystallization occurs during the cooling process.
- Store parts to be annealed in a dry environment (e.g. passive dry box) before annealing. In humid conditions, placing ‘wet’ parts directly into the sand can cause clumping of the quartz.

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7. Annealing Sample Kit

The annealing sample kit is available upon request. It contains five ISO 20795 flexural test specimens prepared using Annealing Method 2.

The oven is set to 180°C, and a k-type temperature probe is placed in the quartz sand. The holding time begins when the sand reaches 165°C. Each specimen is identified by a color code shown in the table below.

DSC testing shows that PEN crystallizes between 154°C and 174°C. The crystallinity values below were measured by XRD.

The green specimen represents the recommended condition. At 55–60% crystallinity, PEN provides the best balance of heat resistance and toughness. Above 70%, the material becomes brittle.

Color Code	Sample Condition	Annealing Process	Crystallinity
None	Not annealed	As printed	0%
Red	Insufficiently annealed	Removed when the silica sand reached 165°C	0%
Black	Initial crystallization	Held for 15 minutes after the silica sand reached 165°C	~15%
Blue	Annealed	Held for 25 minutes after the silica sand reached 165°C	~40%
Green	Recommended condition	Held for 30 minutes after the silica sand reached 165°C	~55%



Revision History

Revision Date	List of Changes	Author	Approval
2025.5.21	Initial release	R. Bourret	K. Chiang
2025.12.8	Add steel plate section as method 3	R. Bourret	K. Chiang
2026.8.13	Updated temperature and time Add annealing sample set	R. Bourret S. Liao	K. Chiang