

Executive Summary

Fused Filament Fabrication (FFF) produced parts exhibit anisotropic mechanical performance due to insufficient interlayer and intralayer chain interdiffusion driven by rapid cooling and steep thermal gradients during deposition. This work presents the development of a novel air-based in-situ annealing system designed to deliver localized thermal energy during printing to improve interlayer bonding and structural uniformity. A modular thermal delivery architecture was developed and integrated into an FFF platform, incorporating controlled airflow, resistive heating, and embedded system control to enable targeted thermal conditioning of recently deposited material. By maintaining temperatures near or above the polymer's glass transition temperature (T_g). The localized nature of the thermal delivery enables effective conditioning of high-performance thermoplastics, providing a pathway toward reducing or eliminating the need for full heated chamber environments in materials such as ULTEM and PEEK.

Background

• Prior In-Process Annealing and Limitations:

In-process annealing has been explored using hot air, rolling, heated contact blocks, infrared, and laser-based methods to introduce thermal energy during or after deposition. However, these approaches are predominantly open-loop, lacking real-time feedback, making optimization across varying geometries and conditions difficult and limiting broader adoption.

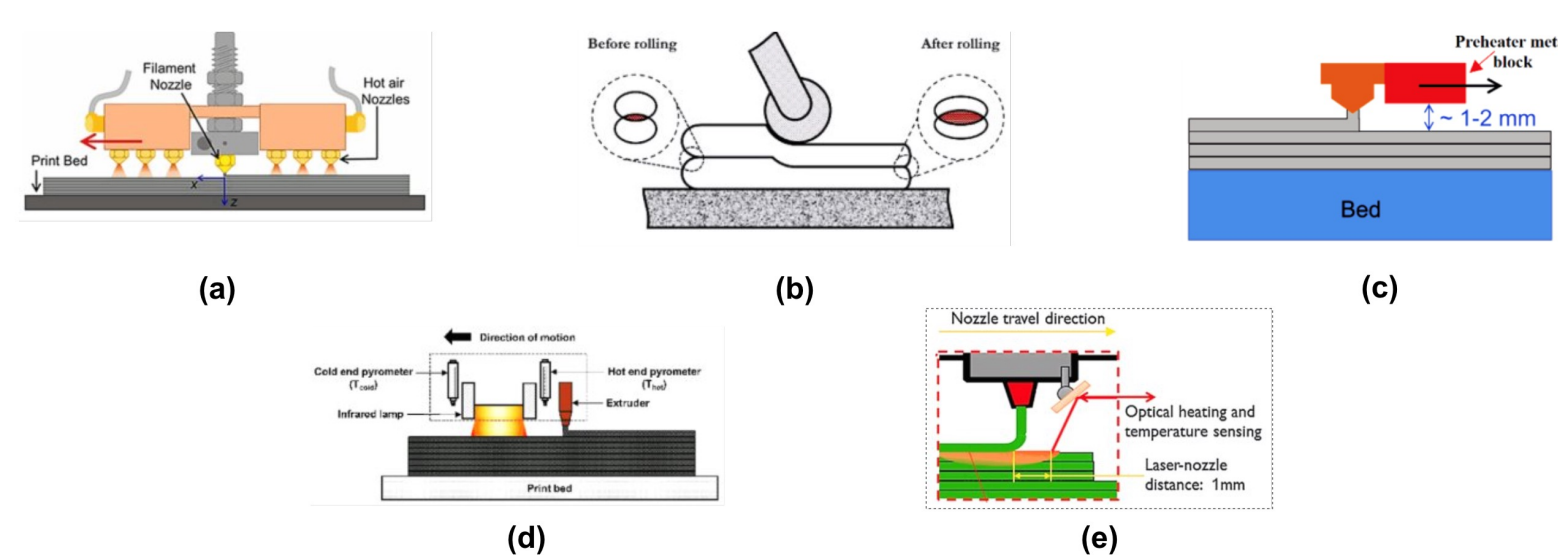


Figure 1. Existing Annealing Systems[1-6]

• Potential of Closed-Loop Air-Based Annealing:

Convective heating delivers a thermal medium directly to the deposition region, enabling rapid response, dynamic adjustment, and localized control. This creates a controllable “thermal envelope,” reducing thermal gradients while quickly adapting to geometric features. Combined with closed-loop control, this approach enables highly adaptive annealing and reduces or eliminates the need for chamber heating.

System Development and Thermal Control Strategy

A localized air-based annealing system was developed to deliver heated airflow to the top 5–10 deposited layers during printing, maintaining temperatures near or above the polymer's T_g . This promotes polymer chain interdiffusion, enhances interlayer bonding, and facilitates stress relaxation within the deposited structure.

The system utilizes a convective heating approach, enabling higher heat transfer rates and improved spatial control compared to radiative methods. This allows for effective thermal conditioning without reliance on globally elevated chamber temperatures.

System Architecture and Control:

- The system allows control over air temperature, flow rate, and direction, allowing precise control over the deposition region,
- Power delivery and control to the air and heating system is given by a embedded control system performing real time adjustment of thermal parameters
- CFD simulations were used to evaluate airflow distribution and iteratively refine system design.
- Detailed system geometry, control strategies, and implementation specifics are partially withheld due to ongoing intellectual property development
- The system is fully operational and supports ongoing experimental validation

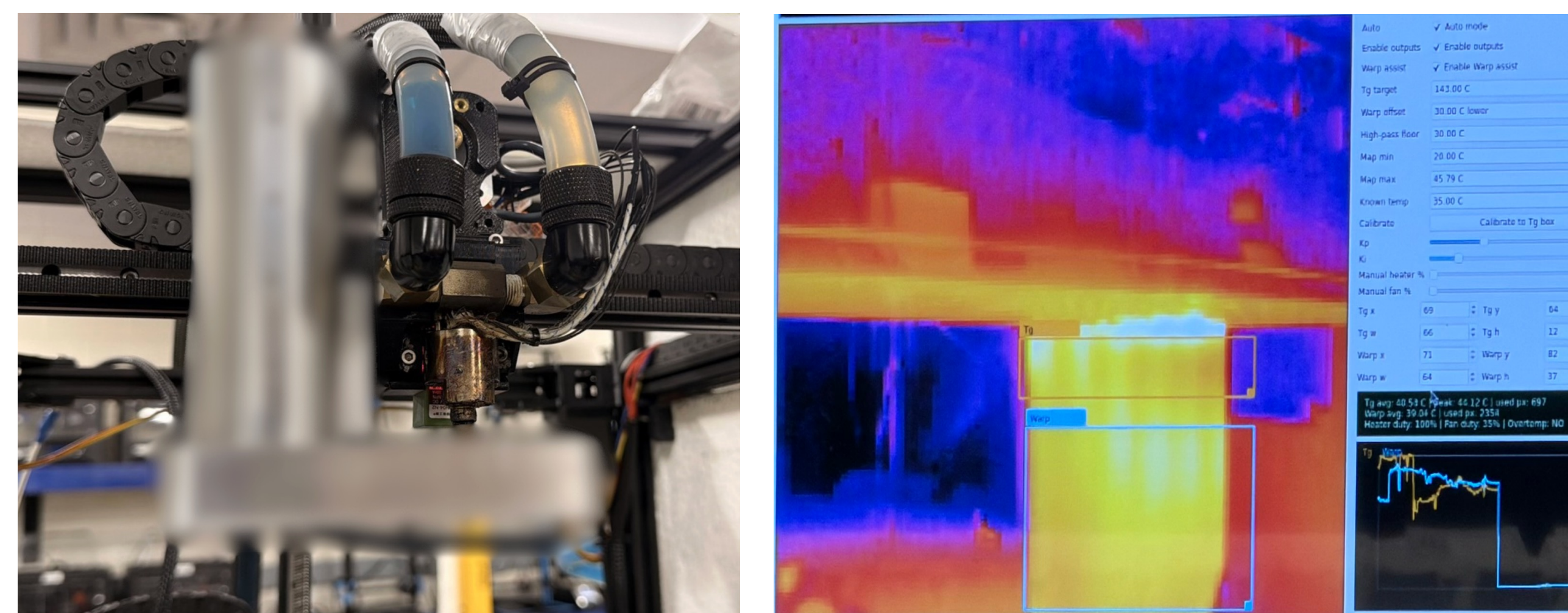


Figure 2. Proposed Annealing System [Left]
Thermal Control Software[Right]

Region Based Thermal Control:

A key component of this work is the implementation of a region-based thermal control strategy, in which distinct thermal zones are maintained:

• Interlayer Diffusion Region (T_g Zone):

A localized region near the deposition interface is maintained at or slightly above T_g to maximize polymer chain mobility and interlayer diffusion.

• Dimensional Stability Region (Warpage Control Zone):

Surrounding material is maintained at a lower temperature to reduce thermal gradients, relieve residual stresses, and preserve dimensional accuracy.

This dual-region approach enables simultaneous optimization of interlayer bonding and geometric fidelity, while providing a pathway toward reducing or eliminating the need for heated chamber environments in high-temperature polymer systems.

Design Considerations and Observations:

System-level testing identified several important considerations:

- Spatial constraints near the deposition interface
- Tradeoffs between airflow velocity and thermal uniformity
- Stability of localized thermal gradients during motion
- Limitations associated with low-cost thermal sensing for data collection of high-speed prints.

A primary design tradeoff was identified in the geometric relationship between the thermal delivery system and the nozzle. Increasing the size of the central cutout in the heating region allows for the use of commercially available hot ends and enables stable, low-pressure filament extrusion. However, this configuration reduces the ability to deliver concentrated thermal energy immediately following deposition, limiting annealing effectiveness.

Conversely, reducing the cutout size improves thermal coverage and enables more effective post-deposition heating. This approach, however, necessitates modified nozzle architectures or extended nozzle geometries, which significantly increase required extrusion pressure and introduce additional thermal management challenges, particularly in maintaining heatbreak stability. Preliminary observations demonstrate that controlled airflow can establish stable localized thermal zones and maintain elevated temperatures near the deposition region without reliance on full chamber heating. These results support the feasibility of in-situ thermal conditioning and its potential impact on interlayer bonding behavior.

Conclusions

Current efforts are focused on experimental validation and system optimization, including:

- Mechanical testing of printed specimens (e.g., tensile testing of dogbone samples)
- Development of a custom high-temperature FFF platform to serve as a long-term testbed for the annealing system and to support future student research and coursework involving high-performance polymers
- Assessment of structural isotropy through material characterization process(CT, SEM)
- Further iteration of the design and thermal control software to be highly adaptable to a wider range of materials and geometries.

This work is being conducted with the objective of preparing results for journal and conference publications in following months.

References

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