Design of Vacuum- and Pressure-Compatible Optical and Thermal Camera Modules for Laser Powder Bed Fusion

Mumin Adhami[a], Mateo Garica-Sandoval[a], Thienan Hoang[a], Matt Whetham[a], Yanzhou Fu[a,c], Can Sun[a], Austin R.J. Downey[a,b], and Lang Yuan[a]

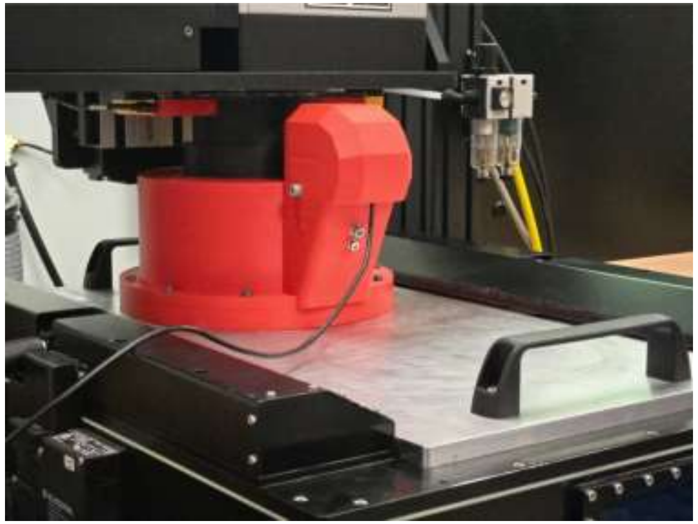
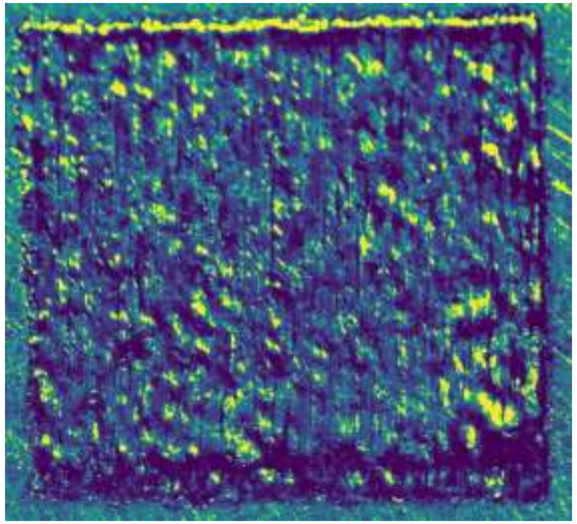
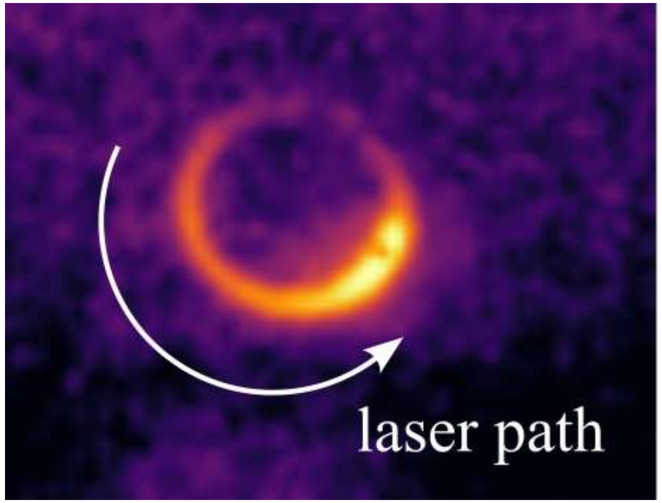
[a]Department of Mechanical Engineering, University of South Carolina, Columbia, SC, USA

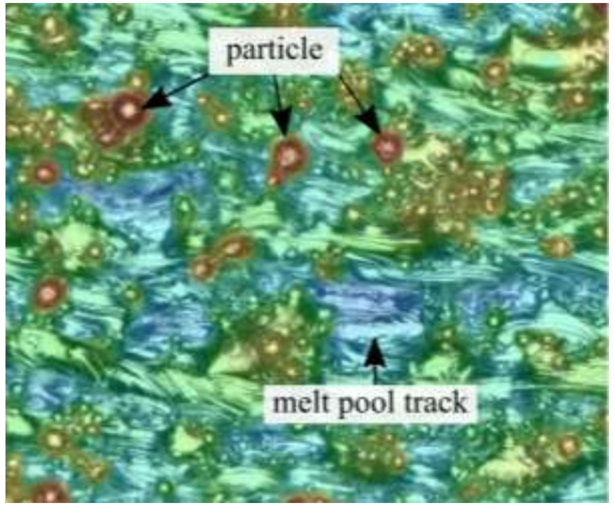
[b]Department of Civil and Environmental Engineering, University of South Carolina, Columbia SC, USA

[c]Engineering and Computer Science Department, Benedict College, Columbia SC, USA

Laser Powder Bed Fusion (LPBF)

- Surface Quality and Melt Pool Behavior
- Prior Work on In-Situ Process Monitoring
- Camera Module Design for Inter-layer LPBF Monitoring

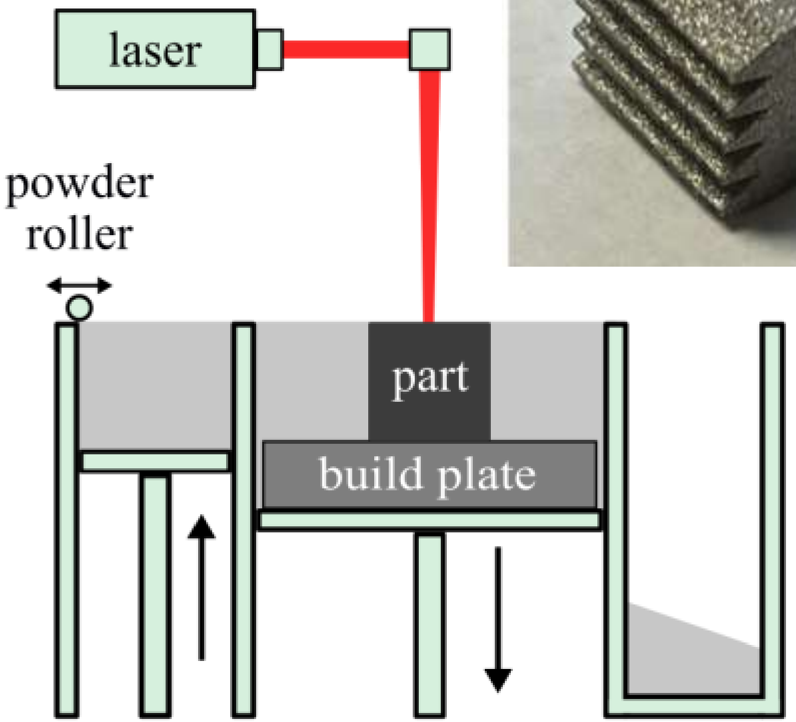




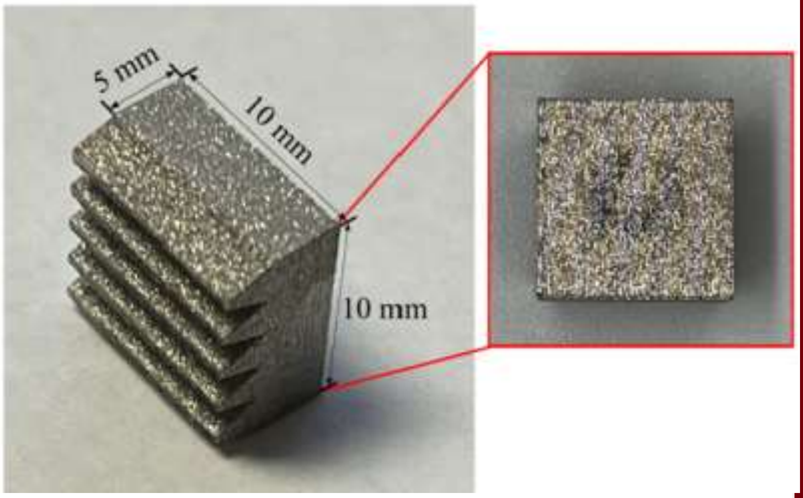


Surface Quality and Melt Pool Behavior

Laser Powder Bed Fusion (LPBF)

- Metal additive manufacturing process using a scanning laser
- Powder is melted layer-by-layer to build complex geometries
- Enables high precision and material efficiency
- Widely used in aerospace, biomedical, and automotive industries

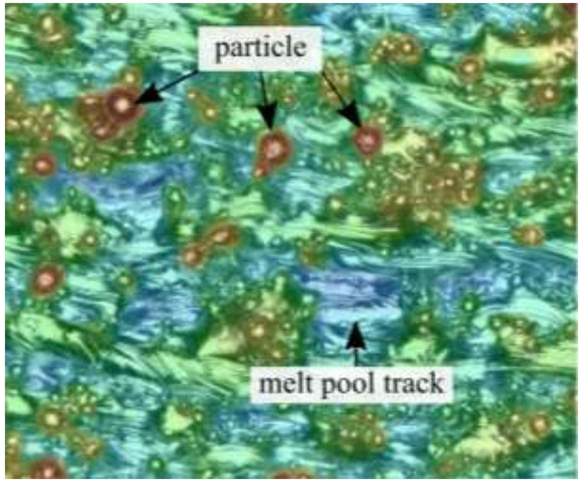




1. https://www.bcn3d.com/introduction-fff-3d-printing-technology-additive-manufacturing-basics/

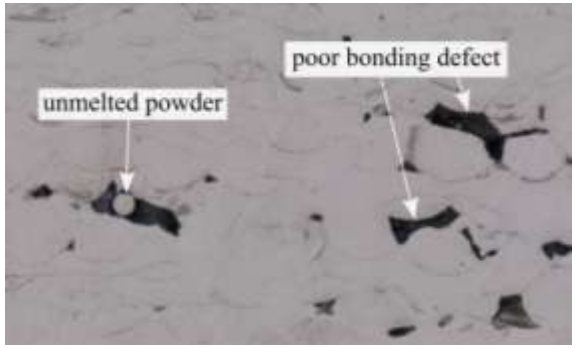
Defects in LPBF Manufacturing

- Process instabilities can introduce internal and surface defects
- Common defects include porosity, keyhole formation, and distortion
- Surface roughness and lack of fusion affect mechanical properties
- Detecting these defects during printing remains challenging

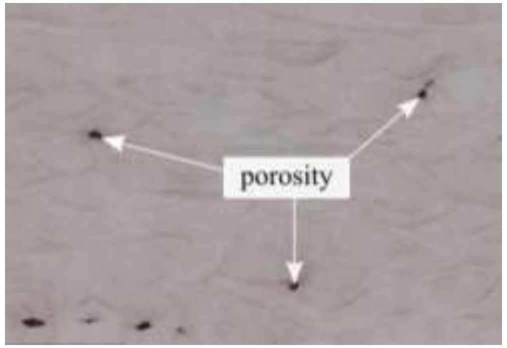


Surface roughness


Distortion



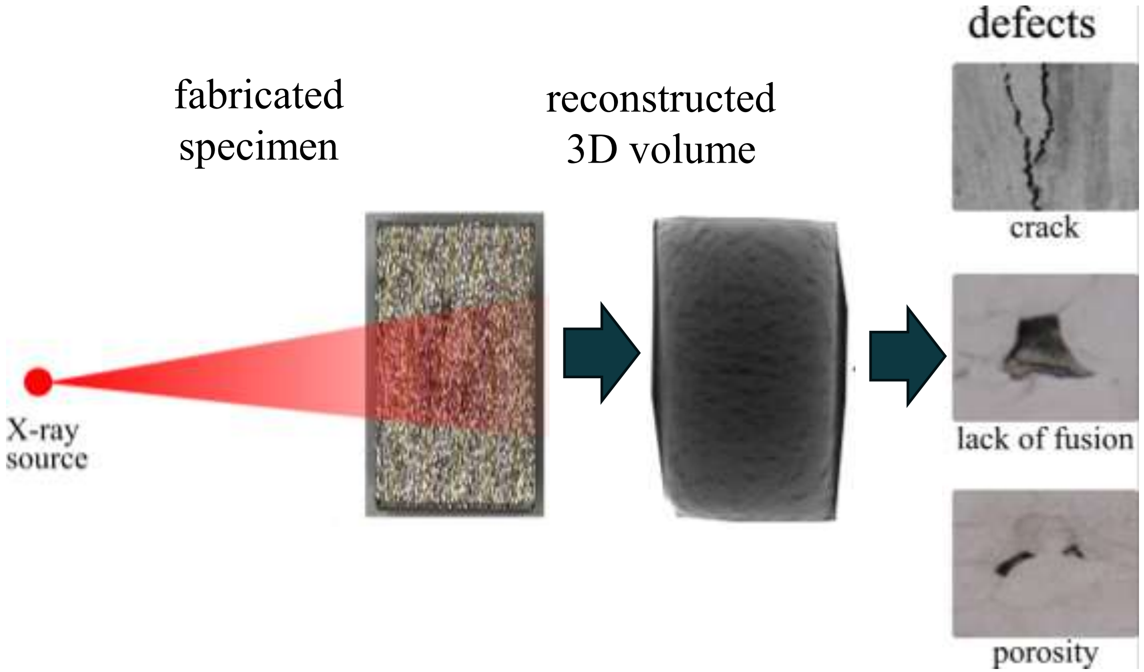
Keyhole



Porosity

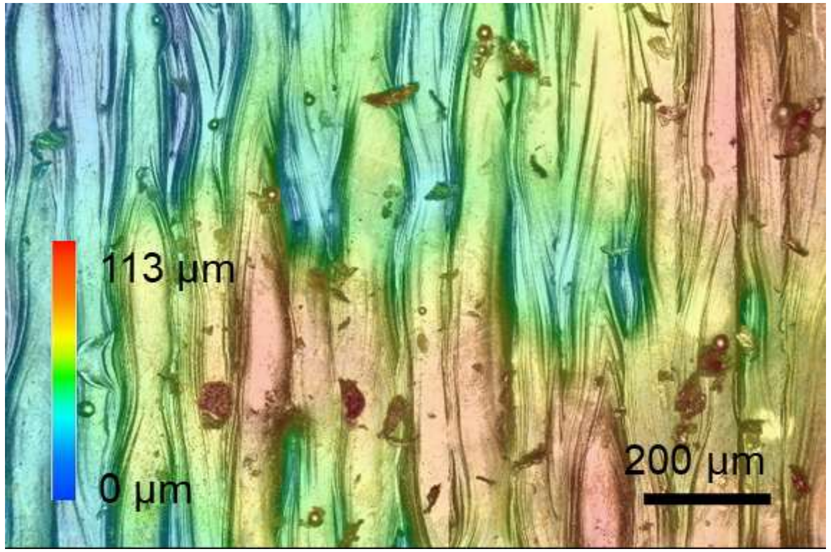
Challenges in LPBF Monitoring

- Defects are typically identified after printing using XCT or microscopy
- Post-process inspection is time-consuming and expensive
- Limited ability to detect defects during fabrication
- Real-time monitoring is needed for improved process control



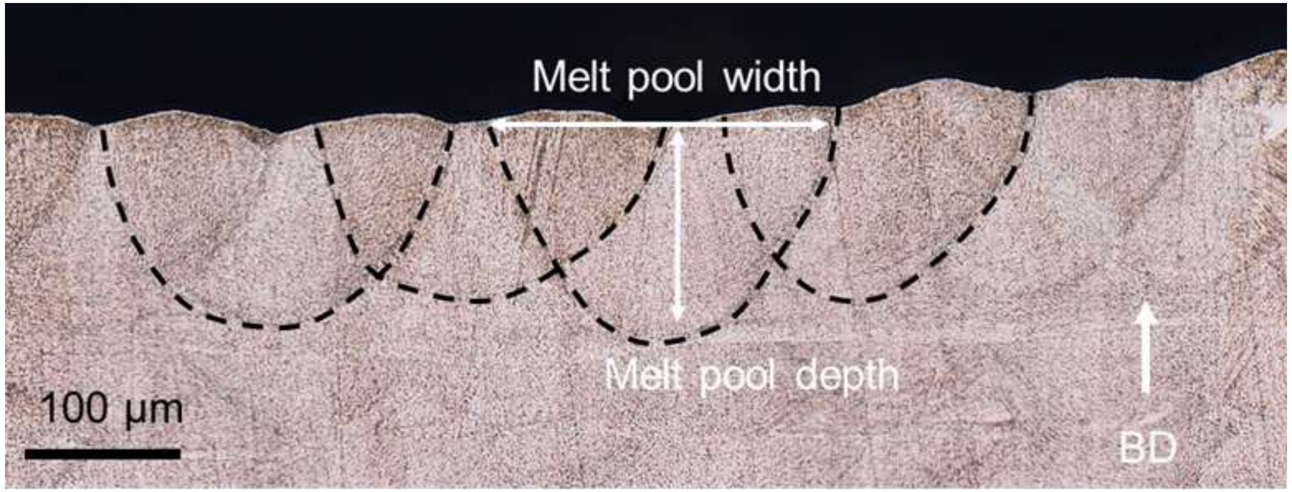
Surface Roughness

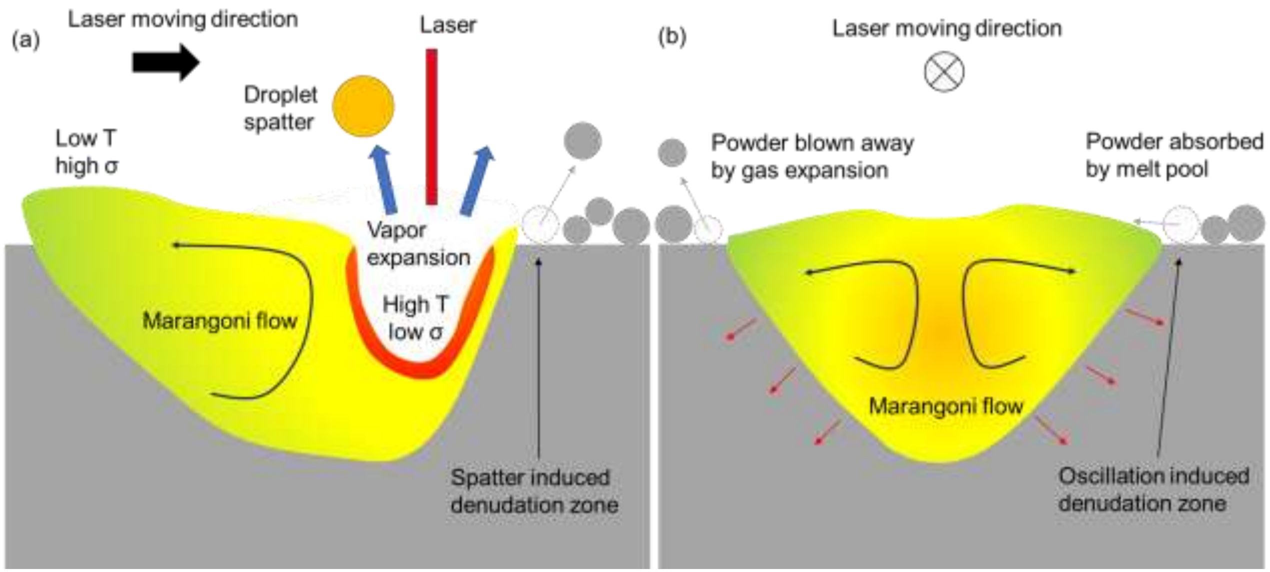
- Surface roughness is a key indicator of part quality and performance
- Strongly influenced by melt pool dynamics and spatter formation
- Low energy input can cause discontinuities and incomplete melting
- Excessive energy can create humps and unstable melt behavior



Melt Pool Stability and Spatter

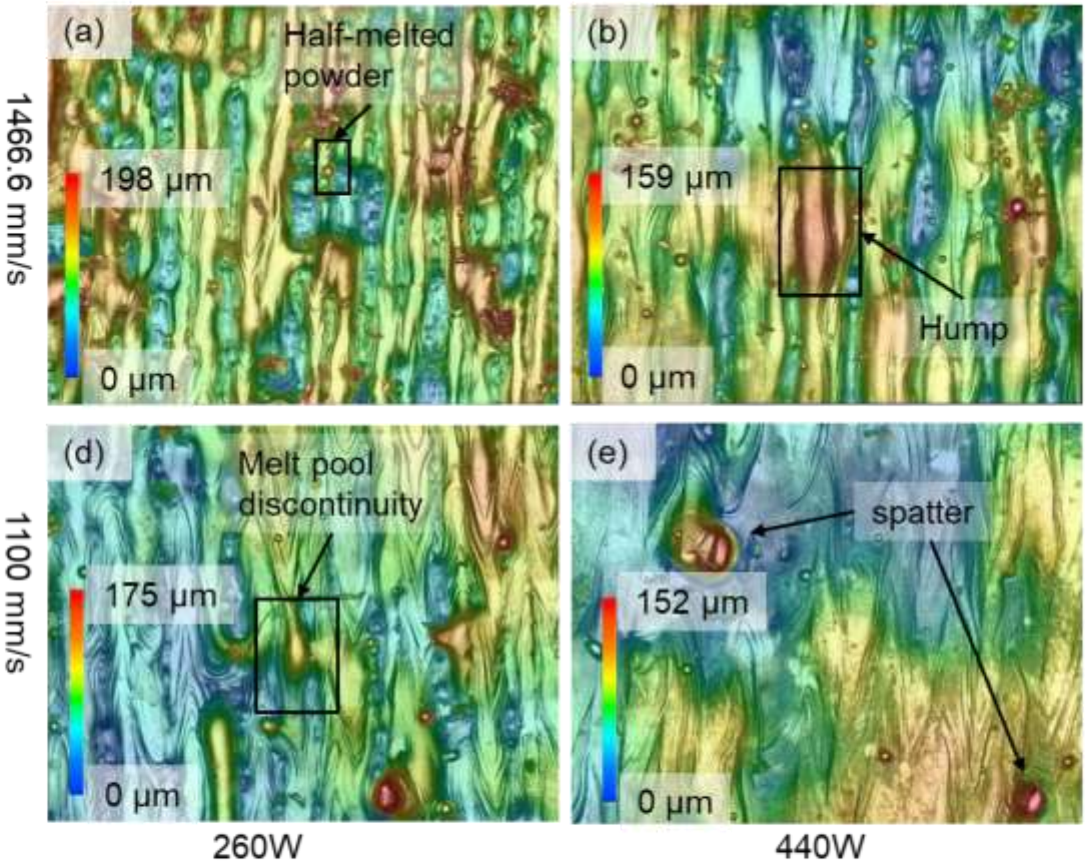
- Melt pool behavior directly affects layer quality
- Stable melt pools produce smooth and continuous tracks
- Instability leads to spatter ejection and irregular solidification
- These effects increase surface roughness and defect probability





Impact of Laser Power on Surface Quality

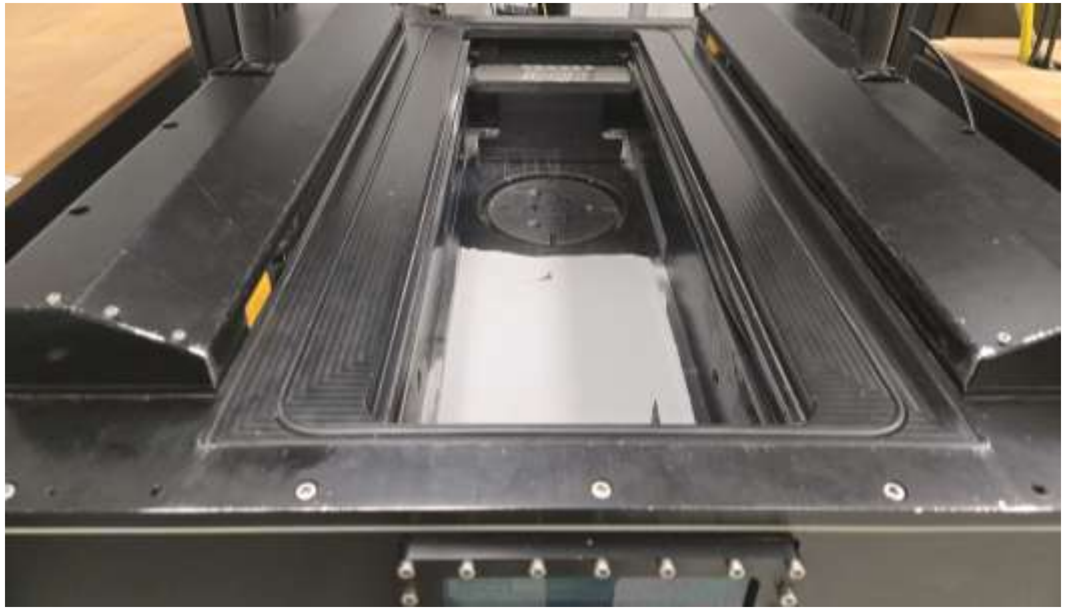
- Low laser power leads to melt pool discontinuities and track gaps
- Moderate power improves melt pool continuity and surface finish
- High power can produce spatter and hump formation
- Optimizing laser power is critical for consistent surface quality



Eliminating melt pool discontinuities, valleys, and spatter improves the top surface quality.

LPBF Printing Chamber Environment

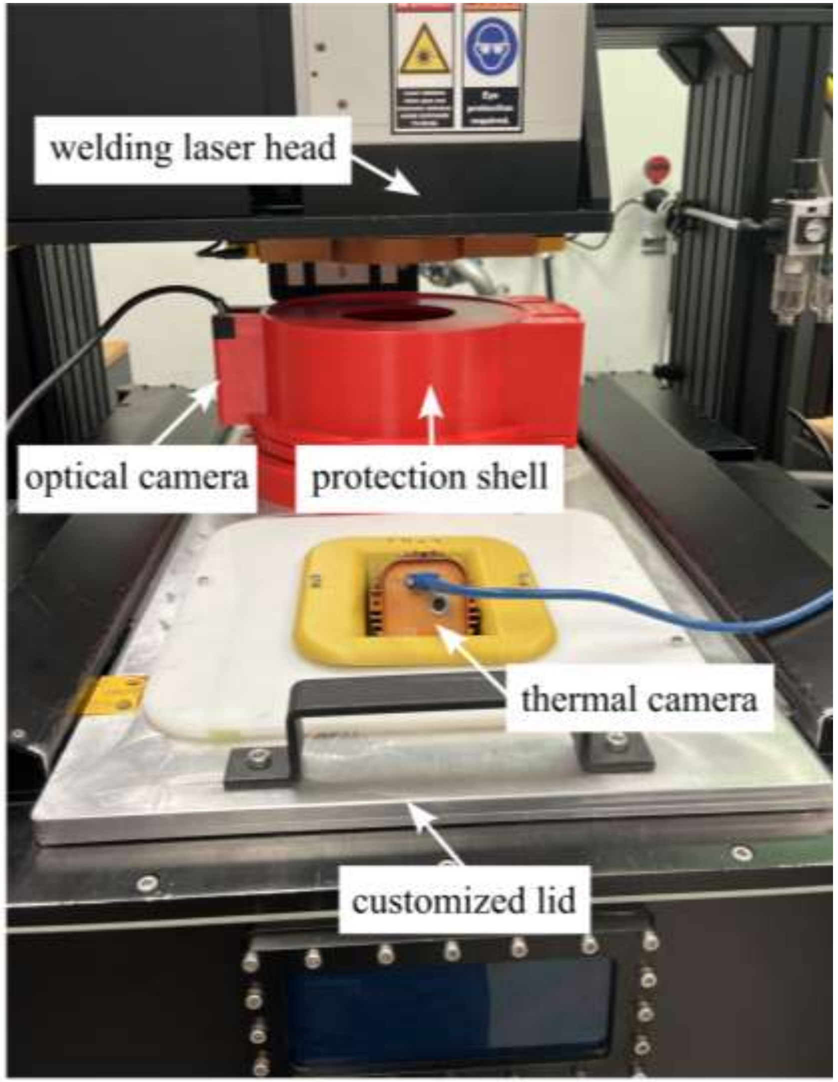
- Printing occurs in a controlled atmosphere chamber
- Inert gases (e.g., argon) prevent oxidation of reactive materials
- Vacuum conditions are relevant for space-based welding
- Optical access must maintain sealing and laser safety



Prior Work on In-Situ Process Monitoring

Experimental Setup for LPBF Process

- LPBF system instrumented with optical and thermal imaging
- Controlled build using 316L stainless steel samples
- Part: 10 mm × 10 mm
- Material: 316L stainless steel
- Printing parameters:
  - Laser power: 200 W
  - Scan speed: 100 mm/s
  - Laser spot size: 100 μm
  - Hatch distance: 100 μm

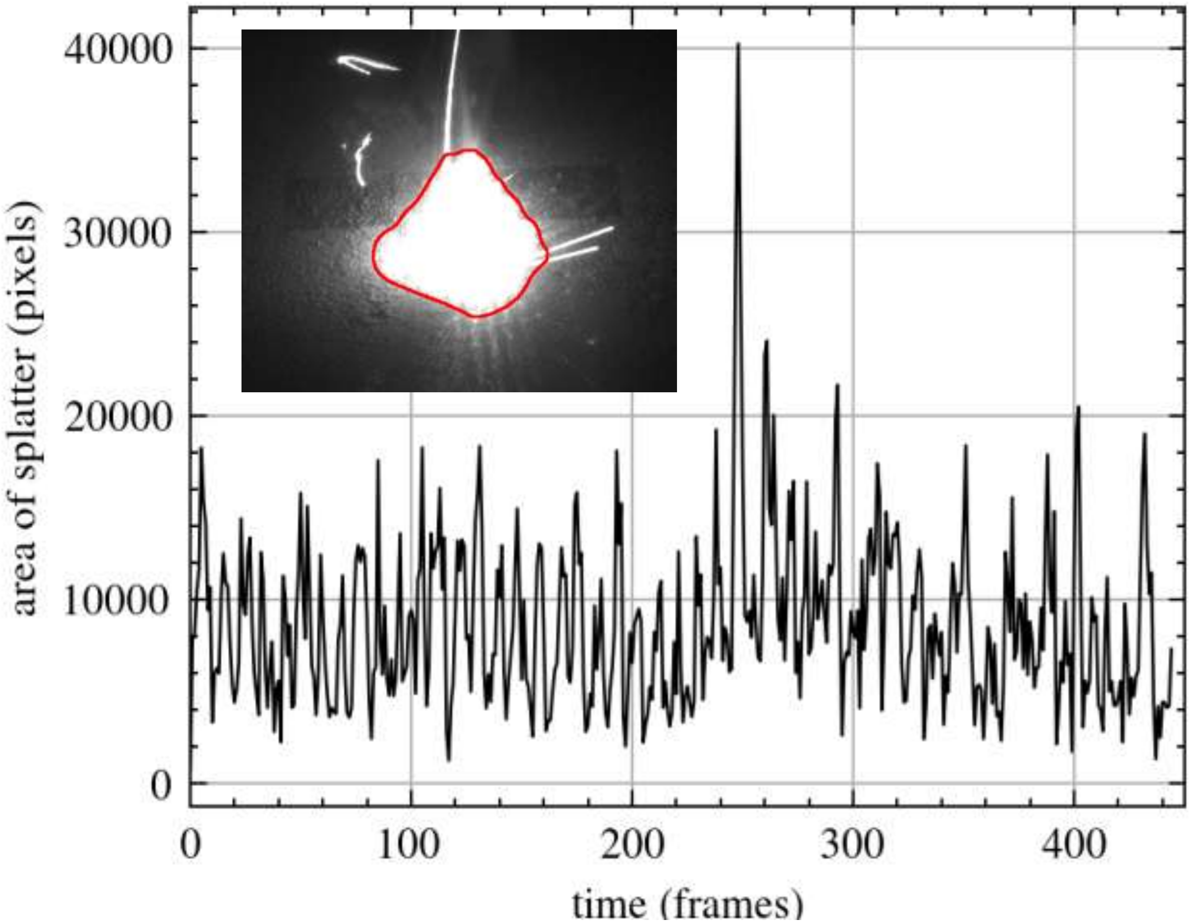


Imaging of LPBF Welding Process

- Captured using a FLIR Blackfly USB optical camera (1440 × 1080 resolution, 100 fps).
- Tracks melt pool, plume, and spatter dynamics in real-time.
- MidOpt BP660 bandpass filter (640-680 nm) enhances imaging clarity.

Real-Time Weld Feature Tracking

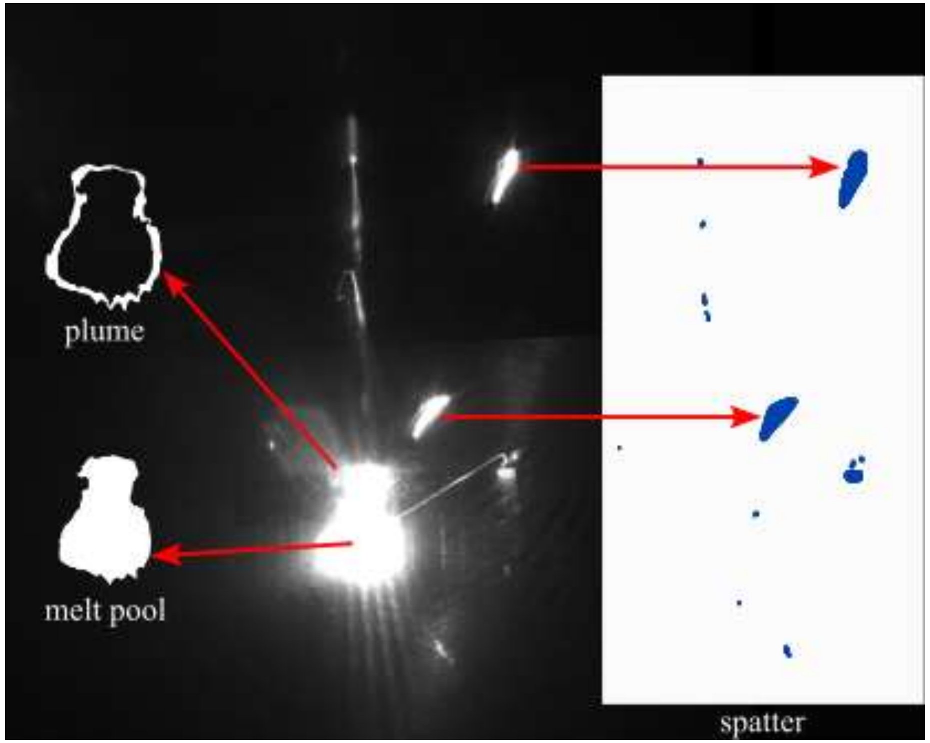
- Image processing used to track the weld/plasma region
- Tracks properties such as area, intensity, and motion
- Captures overall weld behavior, not limited to spatter alone
- Enables real-time monitoring with reduced data complexity

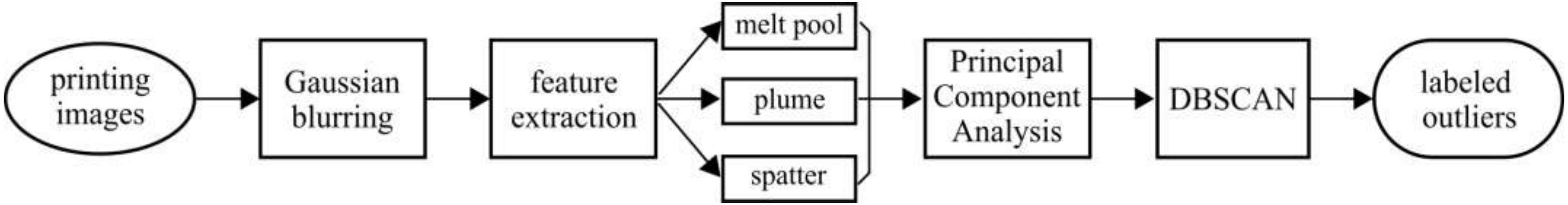


Yanzhou Fu, Braden Priddy, Austin Downey, and Lang Yuan. Real-time splatter tracking in laser powder bed fusion additive manufacturing. In Norbert G. Meyendorf, Ripi Singh, and Christopher Niezrecki, editors, *NDE 4.0, Predictive Maintenance, Communication, and Energy Systems: The Digital Transformation of NDE.* SPIE, apr 2023. doi:10.1117/12.2658544

Feature-Based Process Monitoring

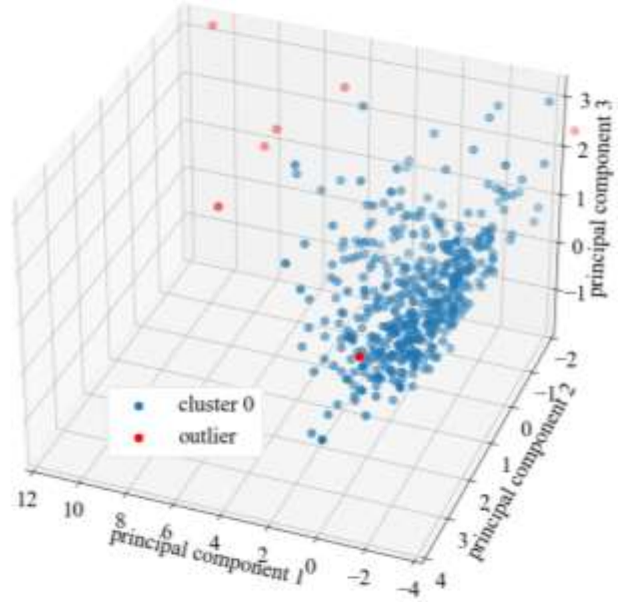
- Multiple features extracted: melt pool, plume, and spatter
- Image preprocessing improves feature segmentation
- Dimensionality reduction (PCA) captures key process variations
- Enables data-driven analysis of printing behavior

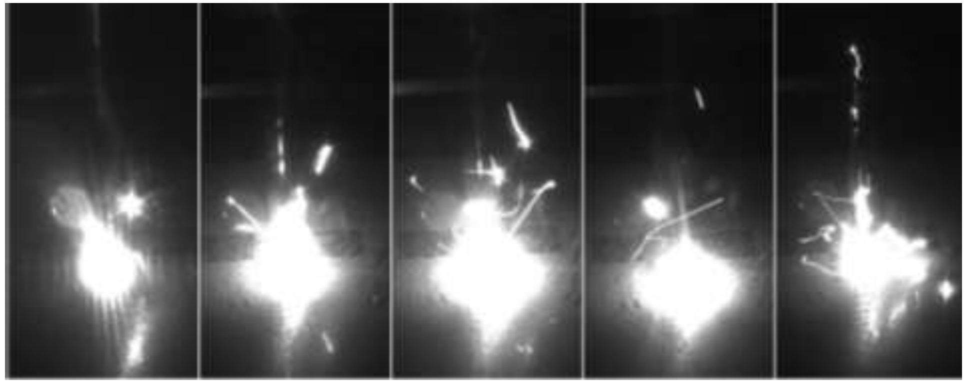




Unsupervised Defect Detection (DBSCAN)

- DBSCAN clustering separates normal and abnormal process states
- Outliers correspond to potential defect formation
- No labeled data required for training
- Demonstrates potential for real-time anomaly detection



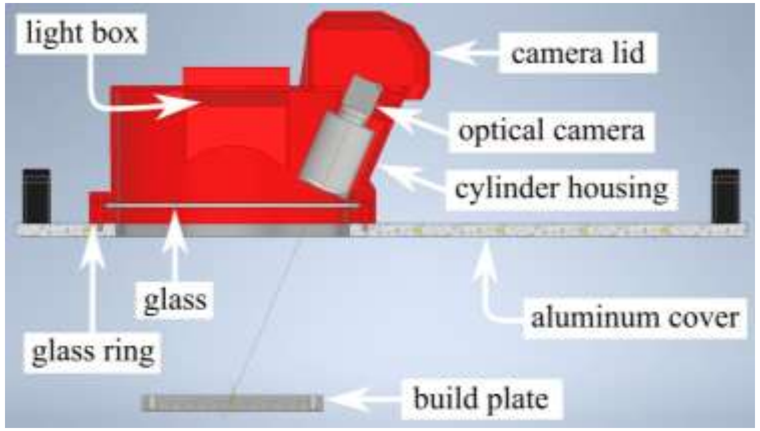


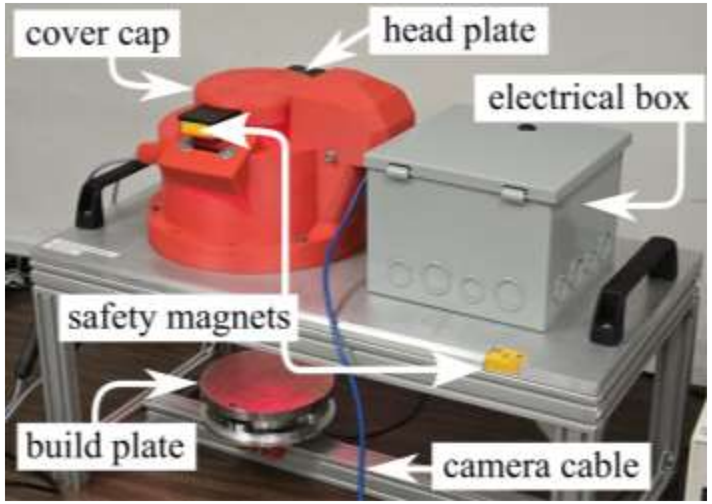
Yanzhou Fu, Matthew Whetham, Austin R. J. Downey, Lang Yuan, and Gurcan Comert. A study of online melt pool, plume, and spatter tracking in laser powder bed fusion using DBSCAN. In Christopher Niezrecki and Saman Farhangdoust, editors, Digital Twins, AI, and NDE for Industry Applications and Energy Systems 2025, page 21. SPIE, May 2025. doi:10.1117/12.3051110

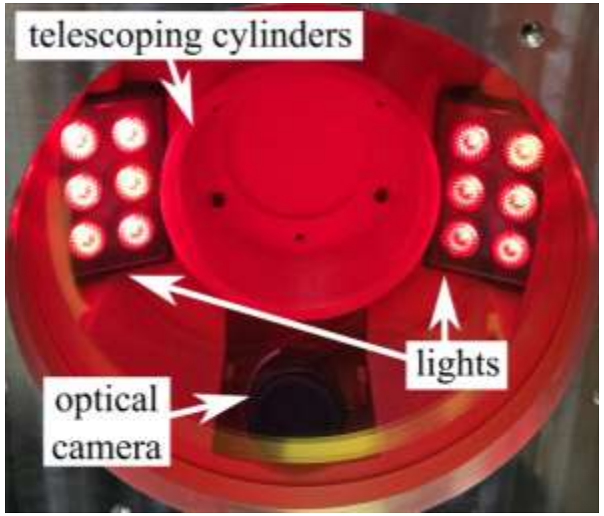
Camera Module Design for Inter-layer LPBF Monitoring

Optical Camera System

- FLIR Blackfly camera, 20 MP resolution
- USB 3.0 interface, 1" monochrome sensor
- 35 mm/F1.8 Edmund Optics lens
- 660 nm bandpass filter, red LED illumination at 625 nm

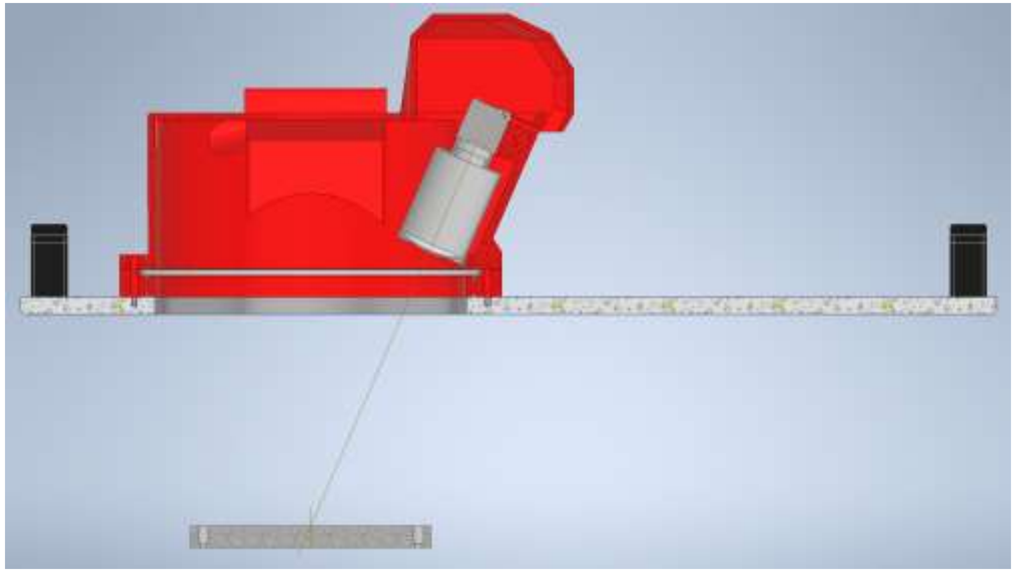


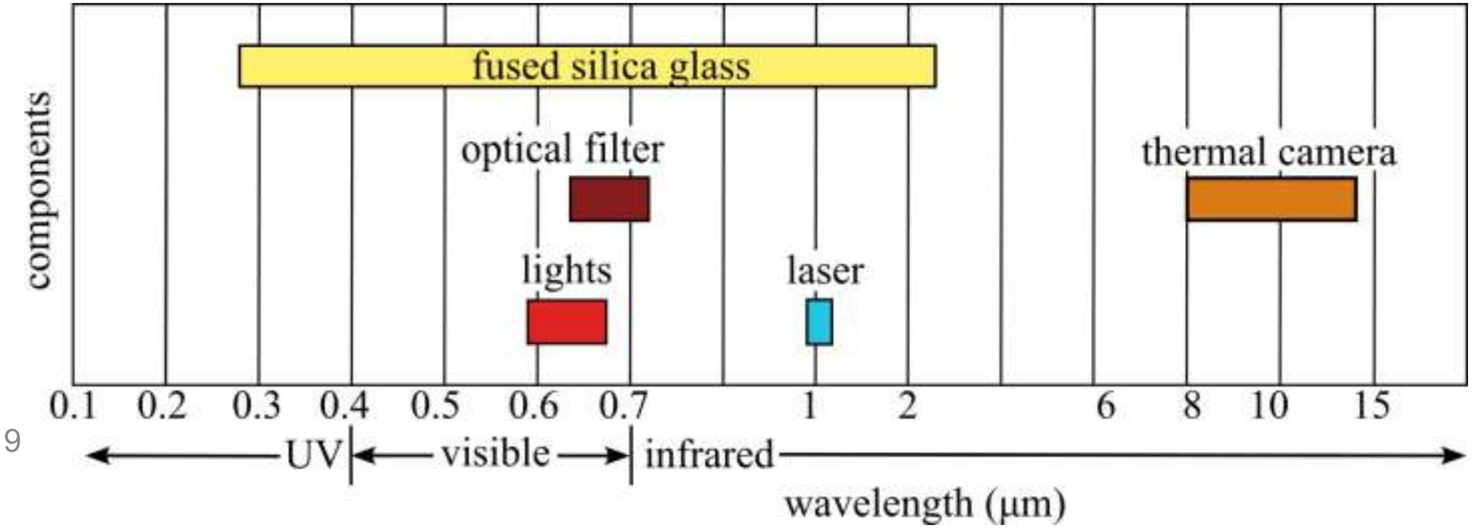


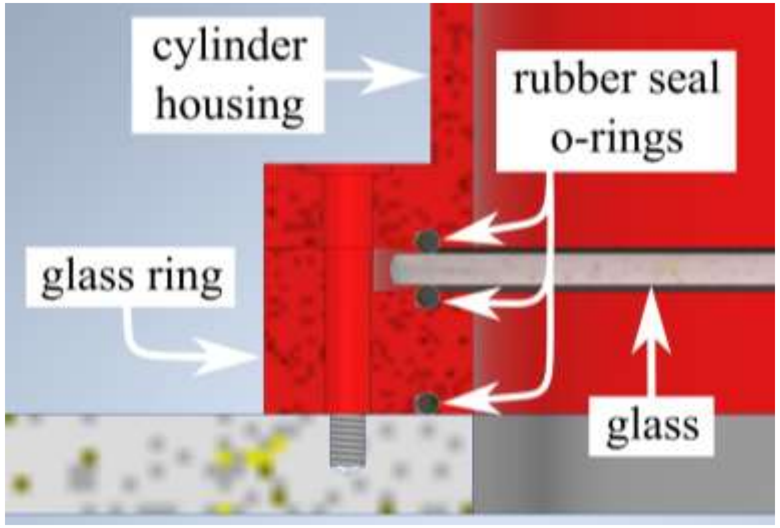


Sealed Chamber Design

- Stable argon gas environment for printing
- Chamber compatible with vacuum conditions if needed
- Sealing achieved with greased rubber o-rings

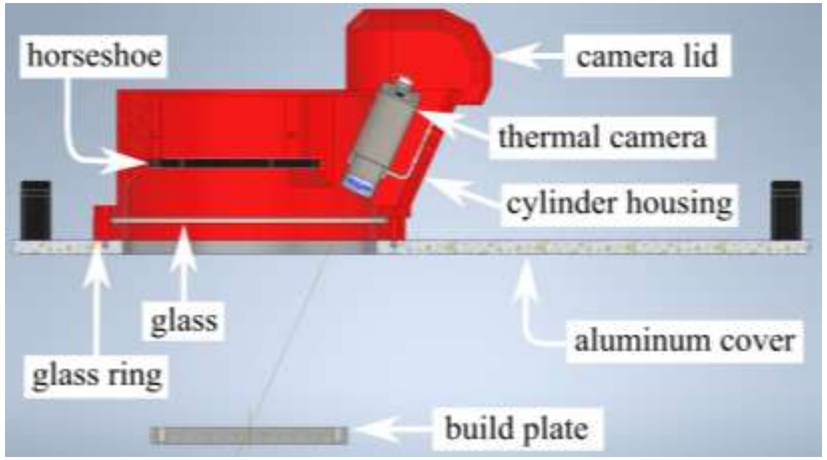


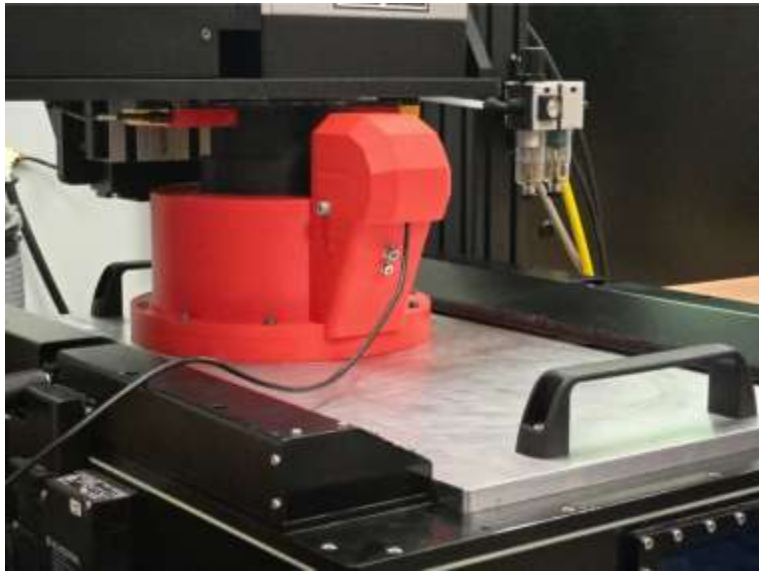


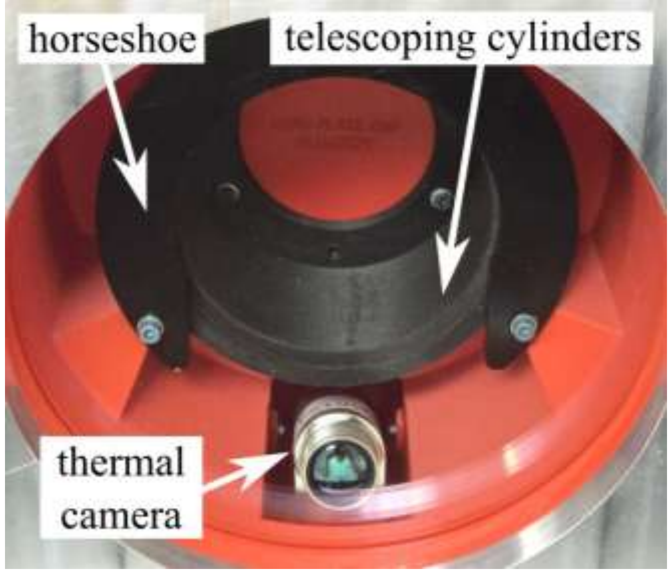


Thermal Camera System

- Optris Xi 400, 382 × 288 pixels
- 80 fps video, 18° × 14° field of view
- Digital focal depth control, USB communication via PIX Connect software

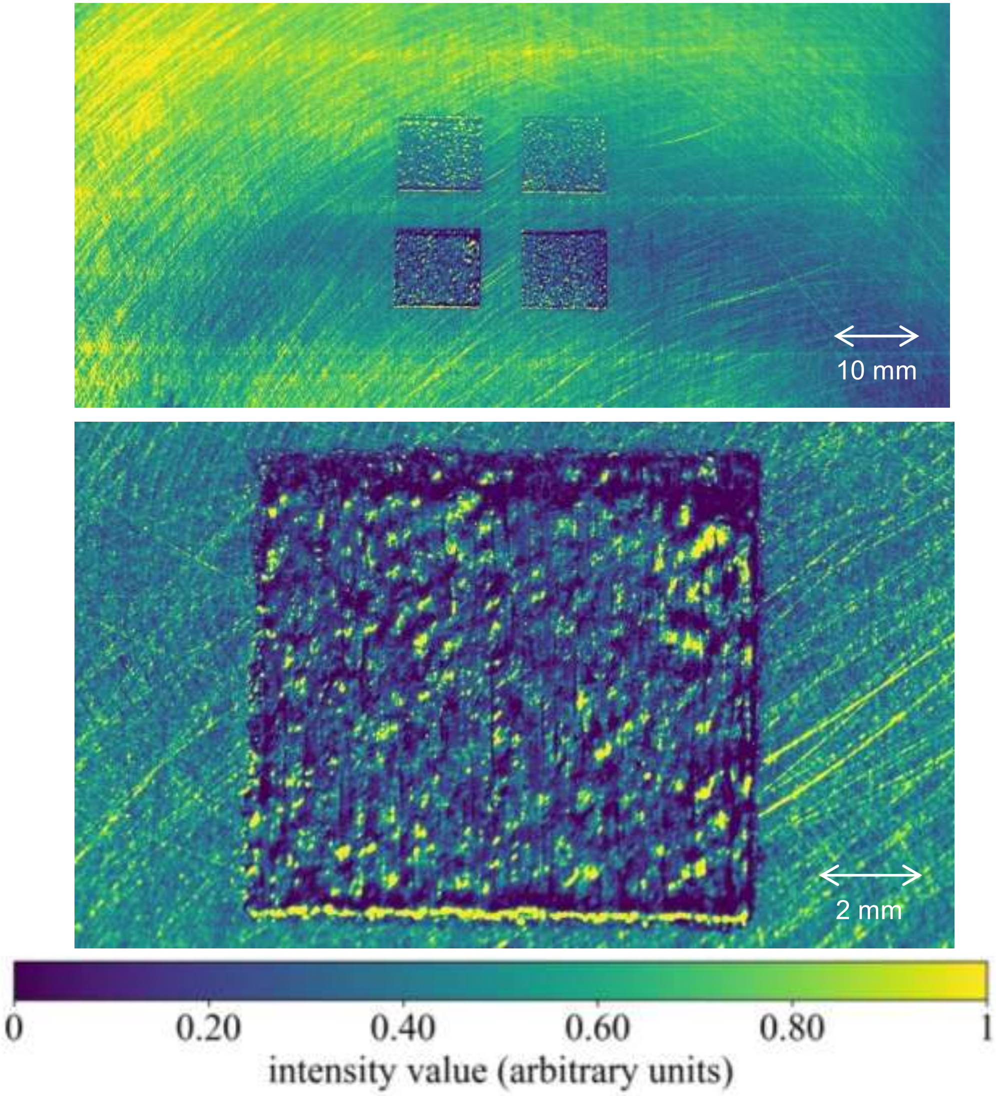






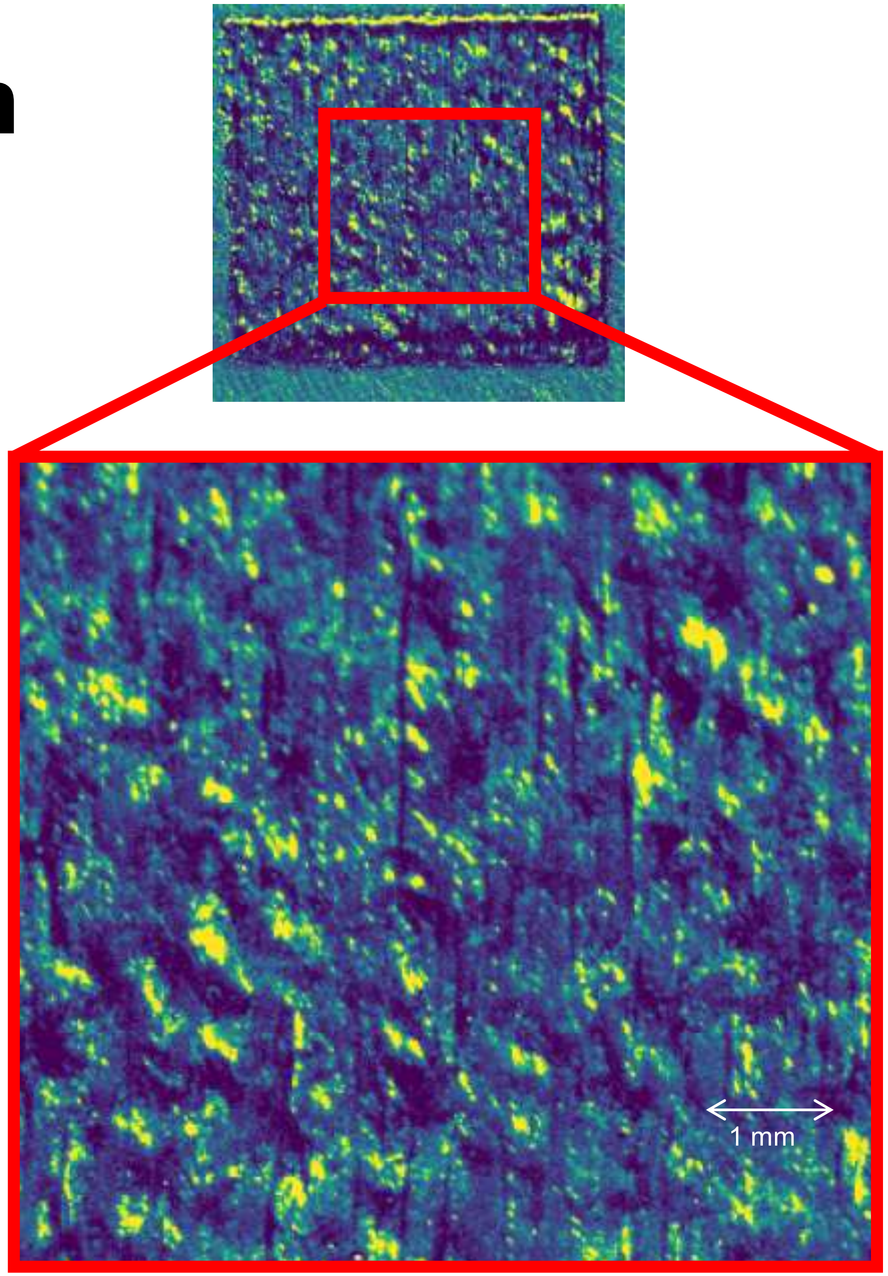
Inter-Layer Optical Imaging

- Captures the build surface after each layer is deposited
- Observes melt tracks, surface morphology, and spatter distribution
- Monochrome imaging enhances contrast of surface features
- Enables layer-by-layer assessment of build quality



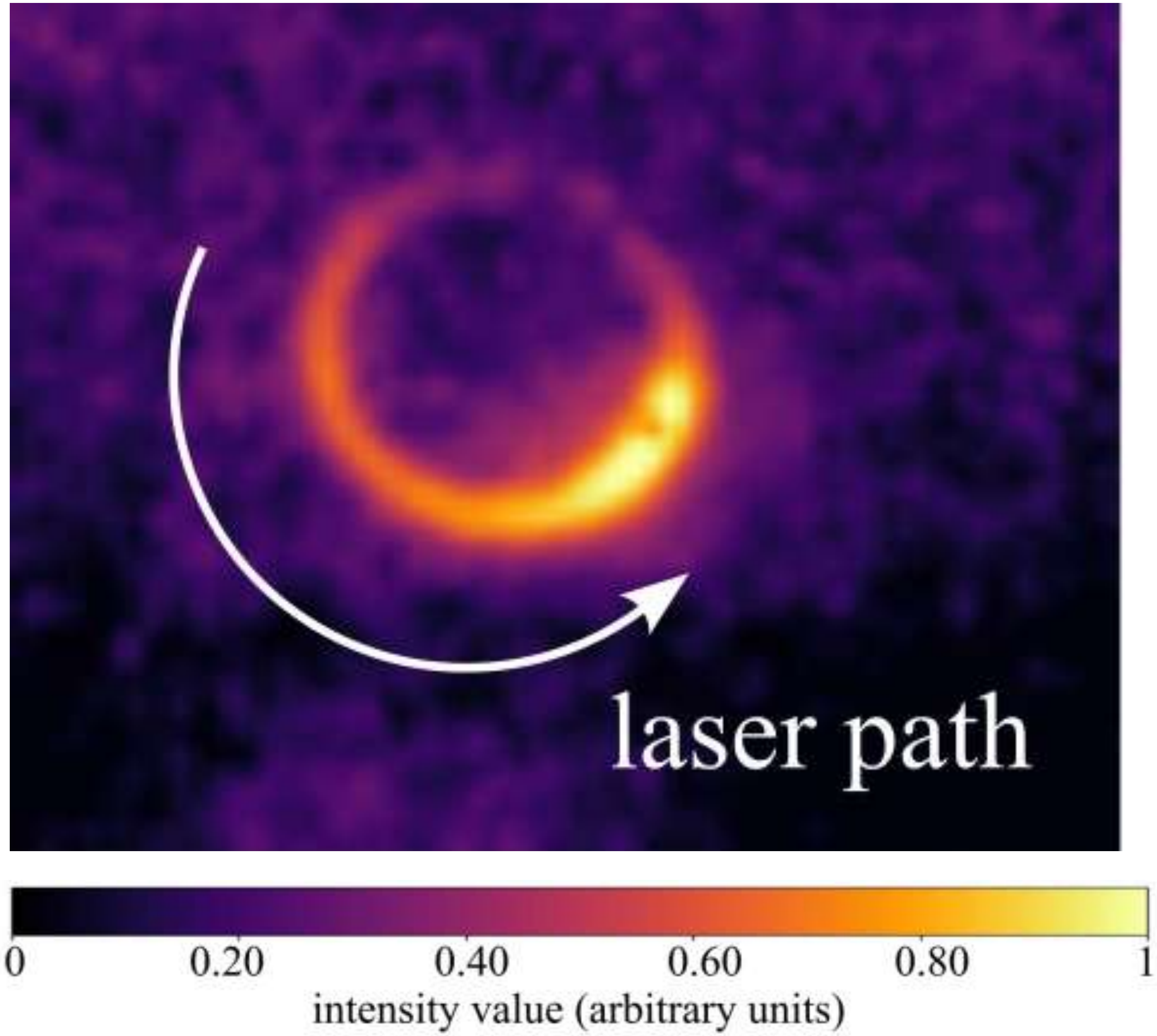
Optical Imaging Resolution

- Sample width: 10 mm field of view
- Spatial resolution: ~50 pixels per mm (20 µm per pixel)
- Individual melt tracks ~15 pixels wide (~300 µm)
- Resolution sufficient to capture fine surface and track features



Thermal Imaging Insights

- Thermal images show relative energy distribution in welds
- Absolute temperature is qualitative due to window attenuation
- Identifies melt pool stability and cooling behavior
- Used to detect anomalies during the build



ACKNOWLEDGEMENT

This research was supported by the United States' National Science Foundation (NSF), USA, Grants Nos. CCF-2503055, and CPS-2237696. This work is also partially supported by the National Institute of Standards & Technology, United States, under grant number 70NANB23H030, as well as the South Carolina Space Grant Consortium under grants 21-117-RID RGP-SC-009, 25-073-REAP-SC-001, and 25-073-BTC-SC-001. Additional support is provided by the United States' National Science Foundation (NSF) through the NSF ASEE Fellowship

Discussion

In Situ Monitoring of Powder Bed Fusion Additive Manufacturing

https://github.com/ARTS-Laboratory/In-situ-monitoring-of-powder-bed-fusion-additive-manufacturing

Author Information
Name: Austin R.J. Downey
Email: austindowney@sc.edu
Lab GitHub: github.com/arts-laboratory

Molinaroli College of Engineering and Computing
UNIVERSITY OF SOUTH CAROLINA