In-Situ Thermal Imaging for Quality Classification of Dissimilar Metal Laser Welds in Battery Tab Welding

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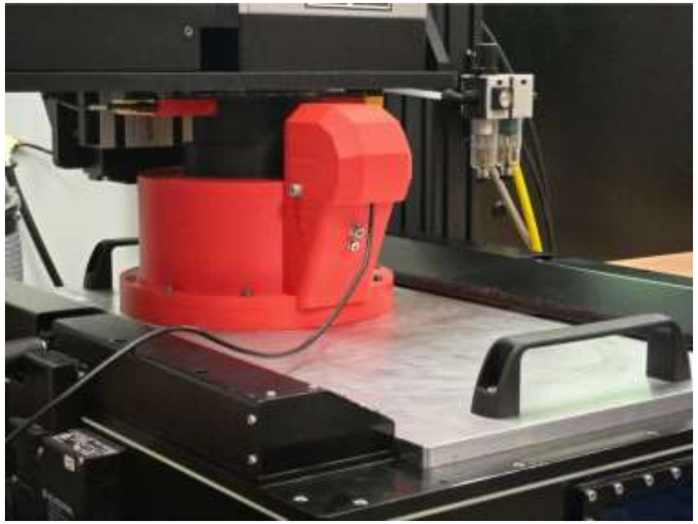
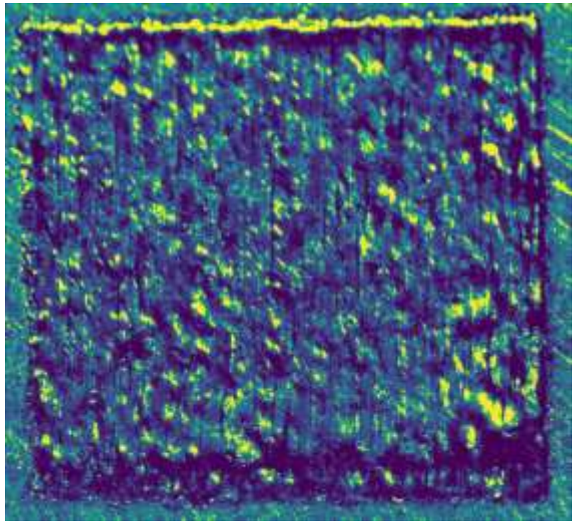
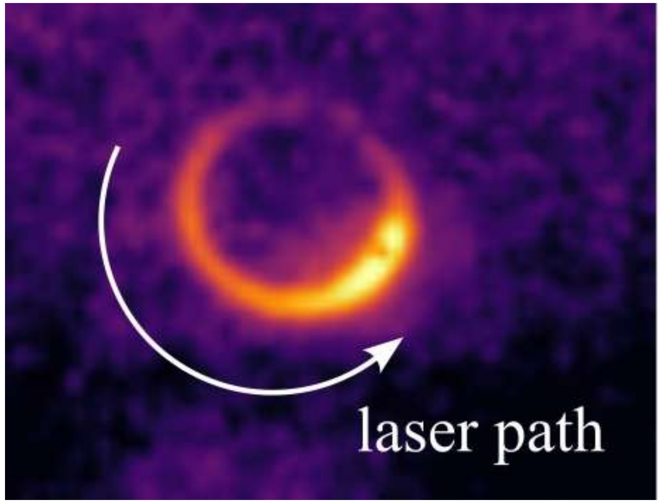
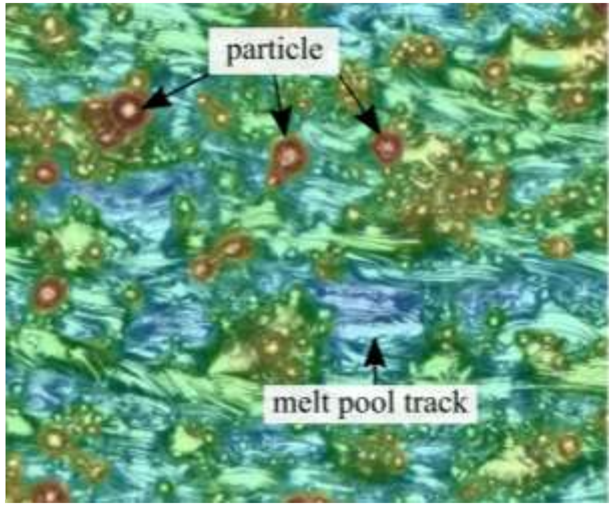
Laser Powder Bed Fusion (LPBF)

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





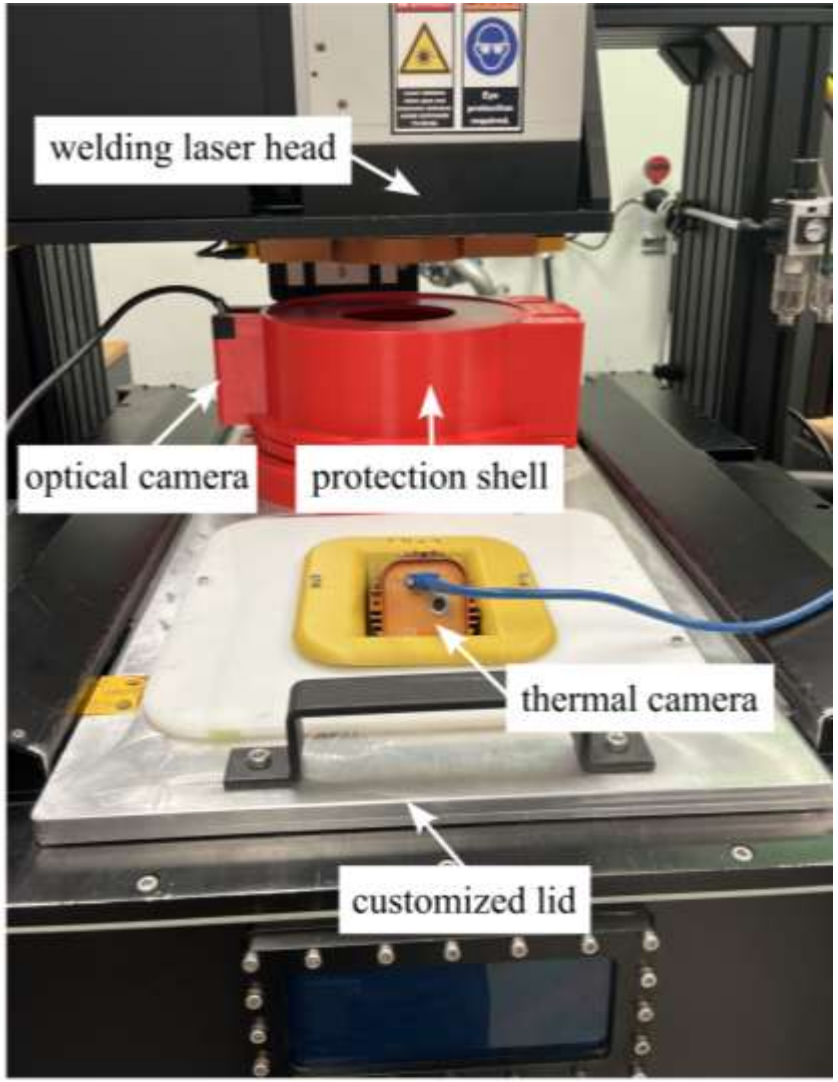




Prior Work on In-Situ Process Monitoring

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

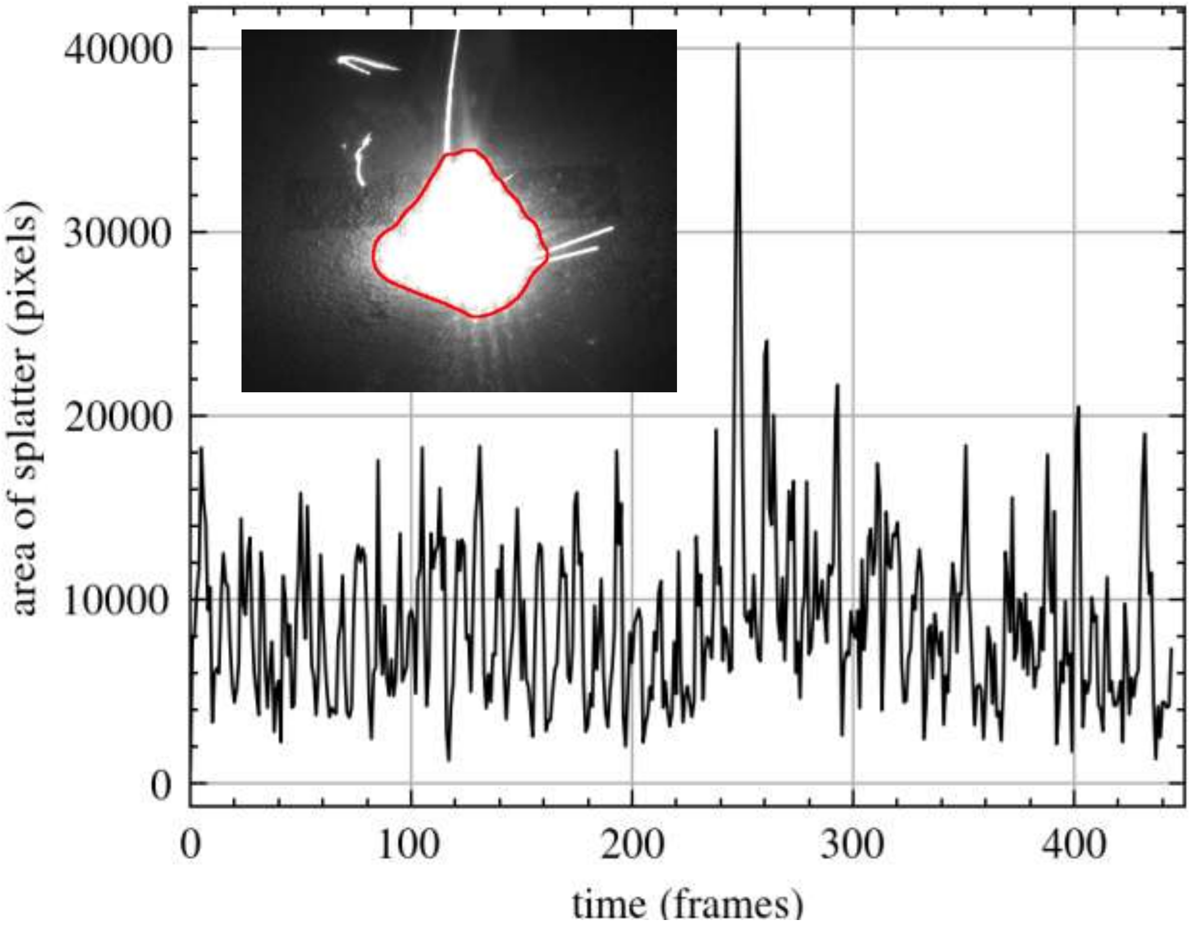


Imaging of LPBF Welding Process

- 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

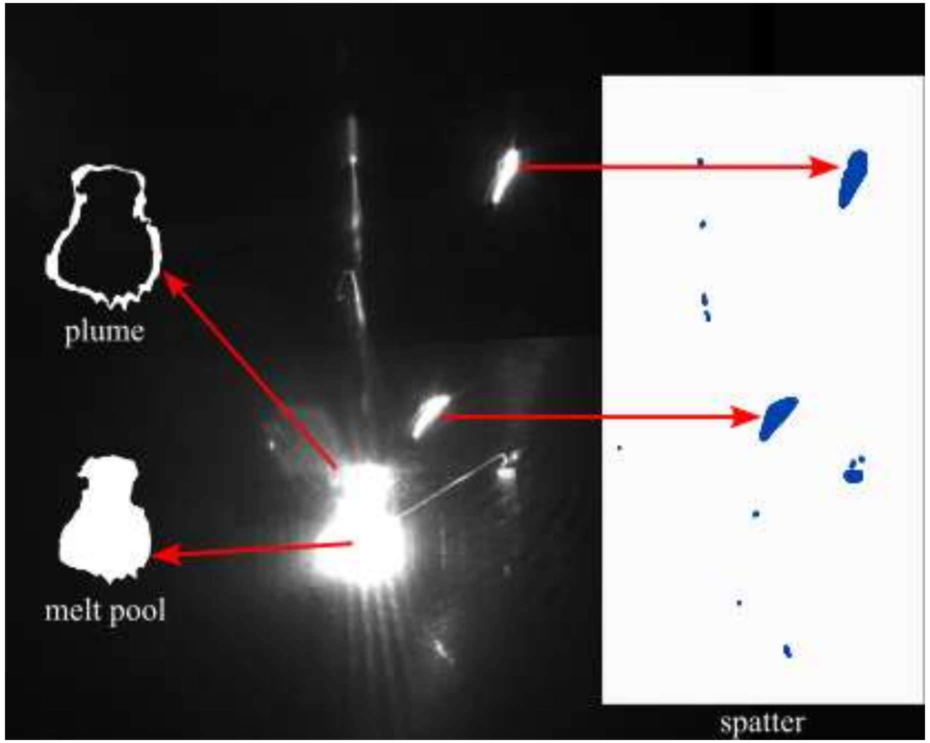
- Image processing used to track the weld/plasma region
- Tracks properties such as area, intensity, and motion
- Captures overall weld behavior, not limited to spatter alone
- Enables real-time monitoring with reduced data complexity

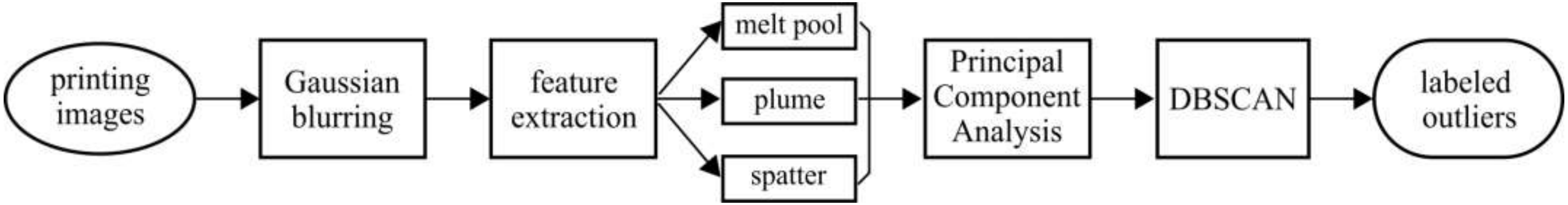


Yanzhou Fu, Braden Priddy, Austin Downey, and Lang Yuan. Real-time splatter tracking in laser powder bed fusion additive manufacturing. In Norbert G. Meyendorf, Ripi Singh, and Christopher Niezrecki, editors, *NDE 4.0, Predictive Maintenance, Communication, and Energy Systems: The Digital Transformation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

Feature-Based Process Monitoring

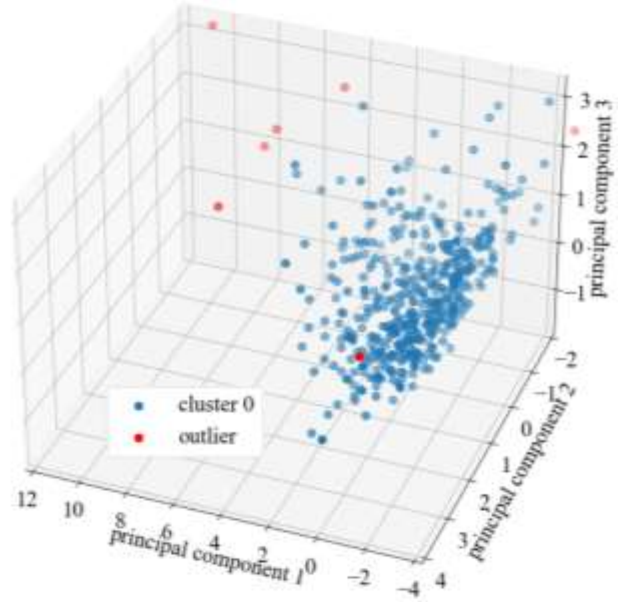
- Multiple features extracted: melt pool, plume, and spatter
- Image preprocessing improves feature segmentation
- Dimensionality reduction (PCA) captures key process variations
- Enables data-driven analysis of printing behavior

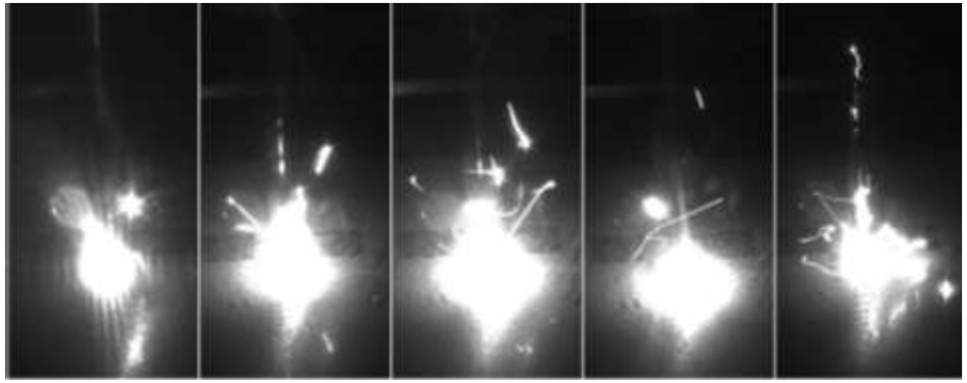




Unsupervised Defect Detection (DBSCAN)

- 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



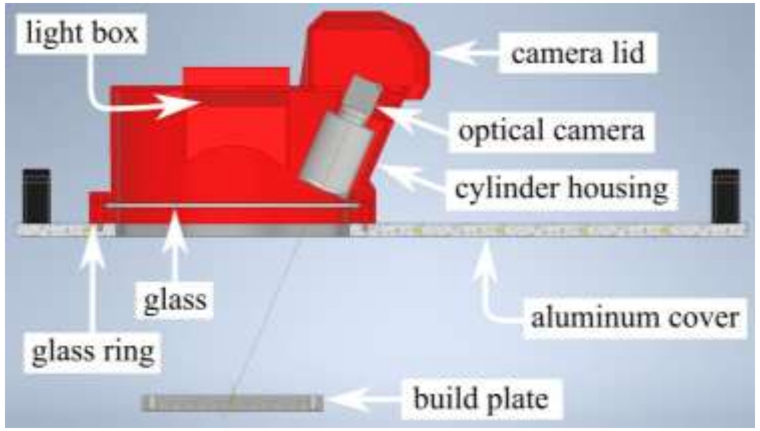


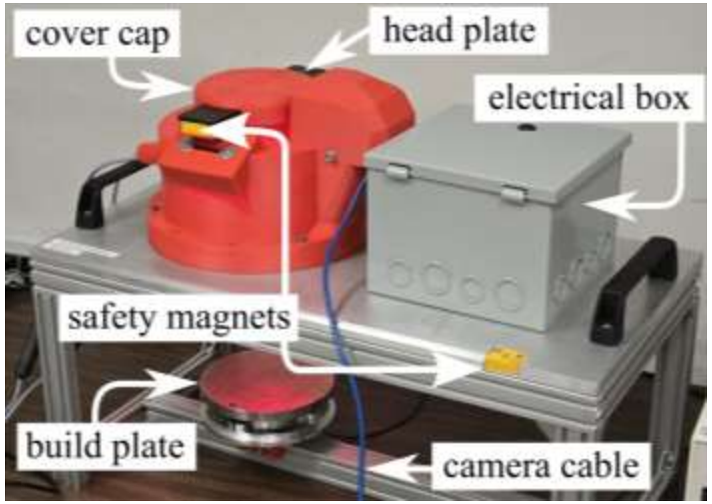
Yanzhou Fu, Matthew Whetham, Austin R. J. Downey, Lang Yuan, and Gurcan Comert. A study of online melt pool, plume, and spatter tracking in laser powder bed fusion using DBSCAN. In Christopher Niezrecki and Saman Farhangdoust, editors, Digital Twins, AI, and NDE for Industry Applications and Energy Systems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

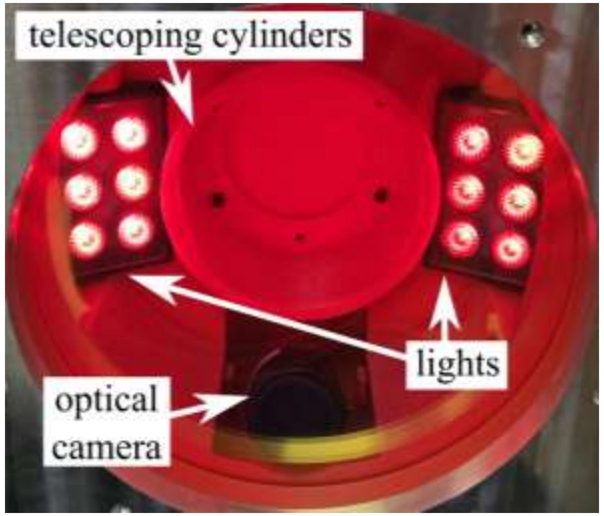
Camera Module Design for Inter-layer LPBF Monitoring

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

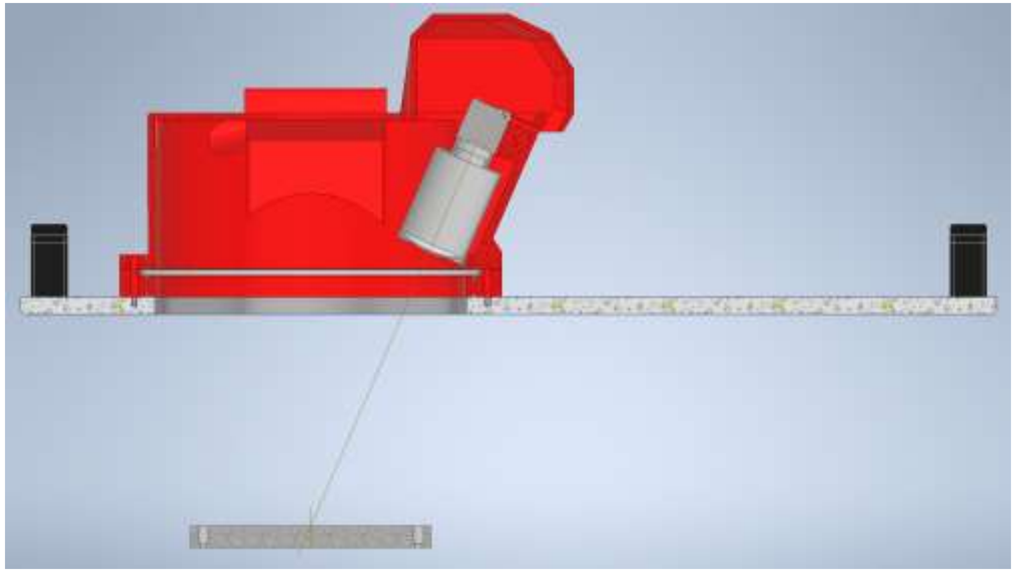


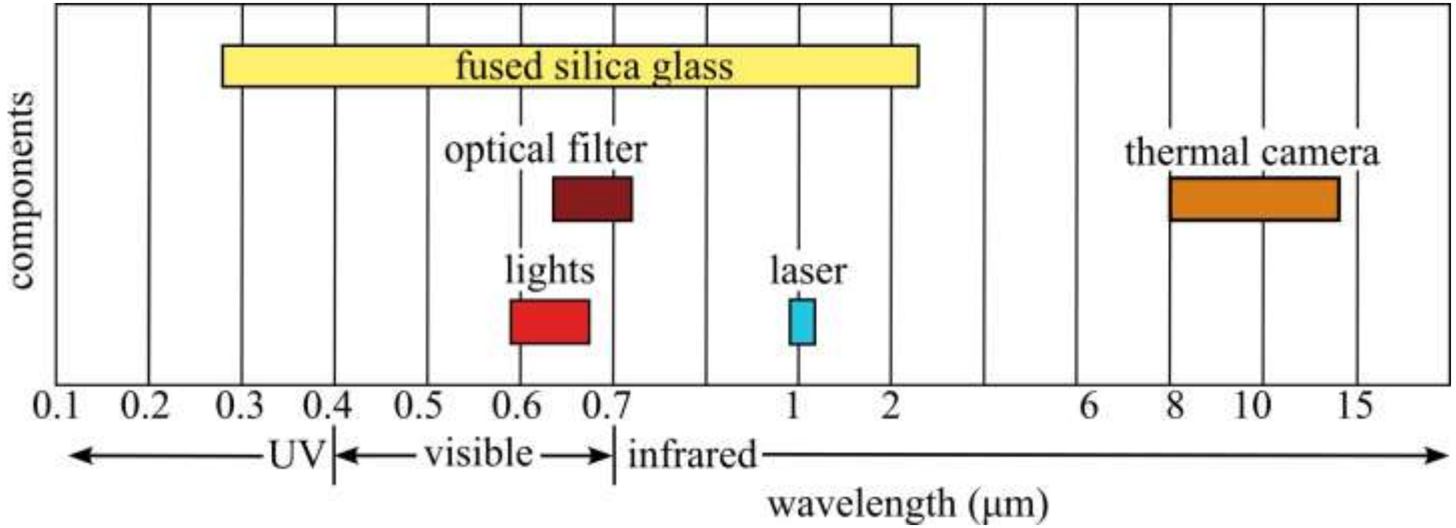


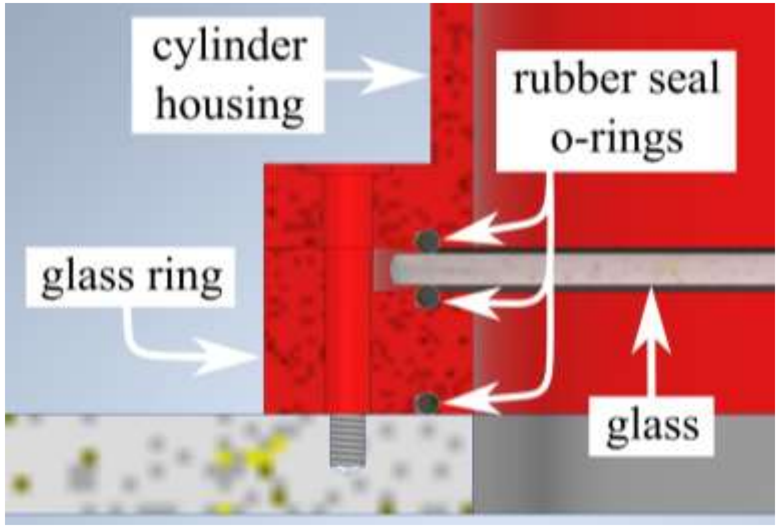


Sealed Chamber Design

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

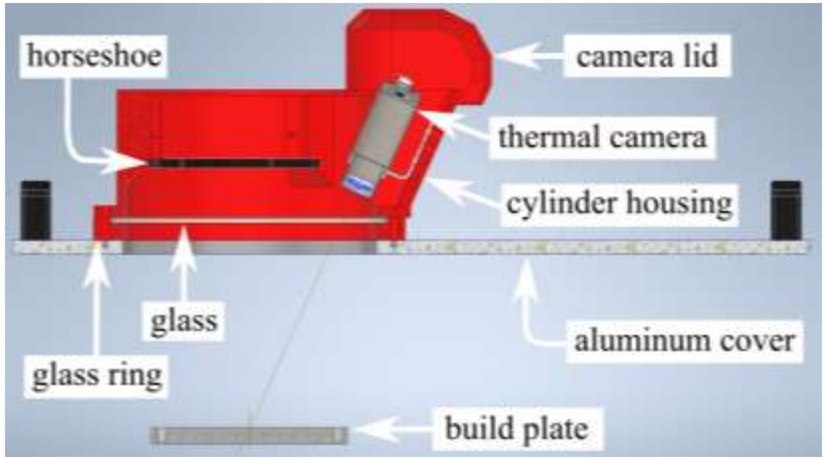


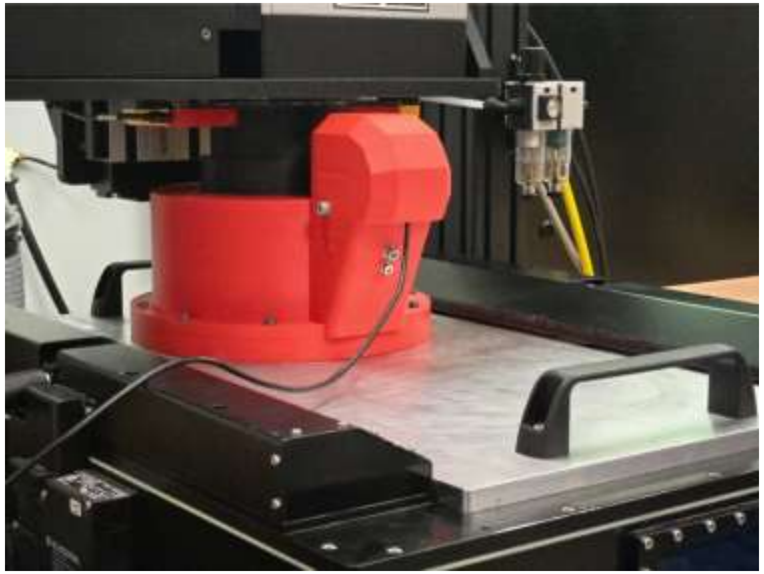


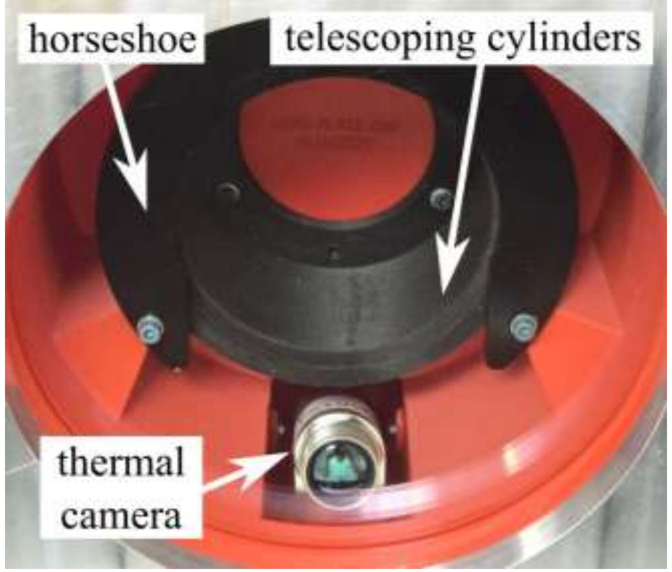


Thermal Camera System

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

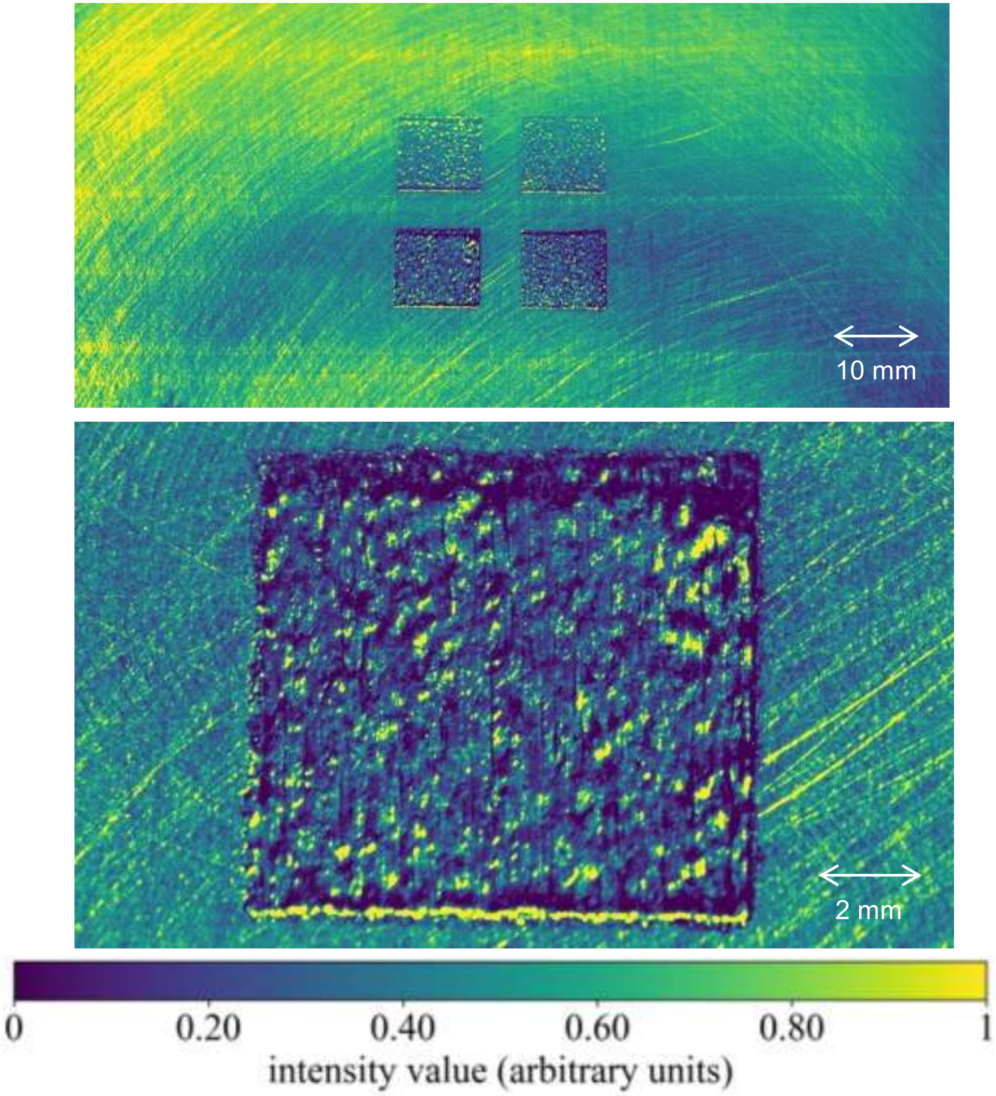






Inter-Layer Optical Imaging

- 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



Utilizing Thermal Imaging for Real-time Defect Detection

Battery Tab Welding

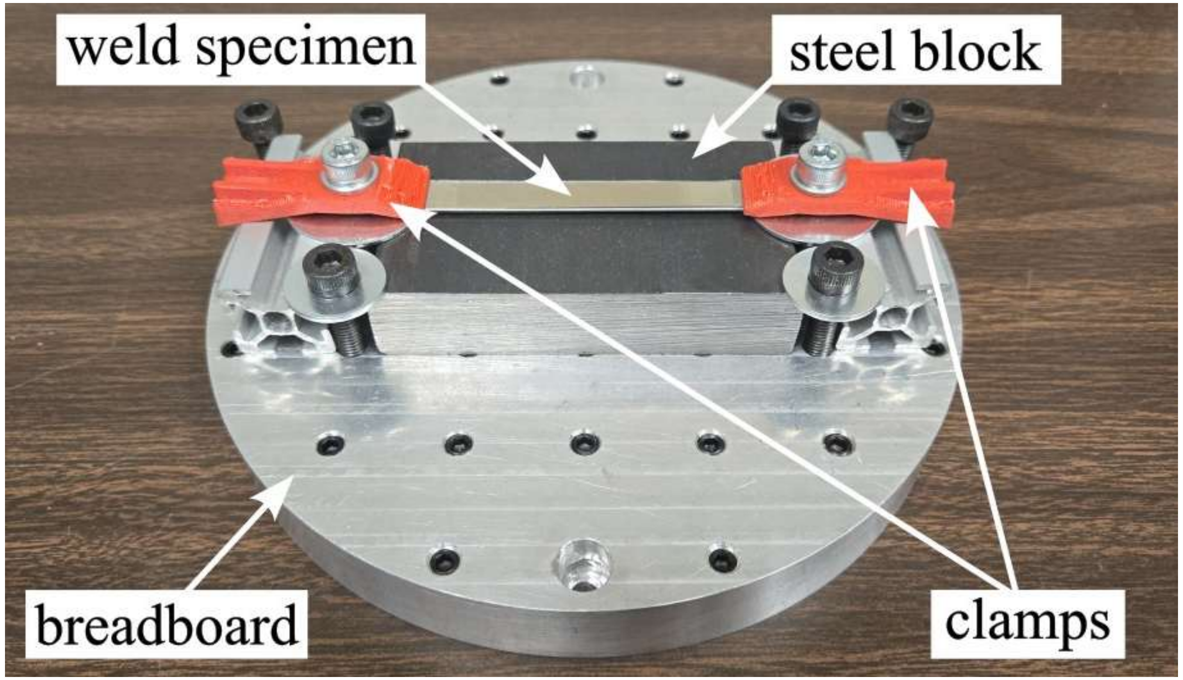
- Traditional battery pack manufacturing follows a cell-to-module-to-pack architecture.
- This approach is now shifting toward direct cell-to-pack integration.
- The long-term objective is to increase weld speed without compromising quality, enabling higher production efficiency and greater profitability.

Cell to Pack manufacturing method that will require high-quality, high-throughput battery tab welding on assembly lines.

https://www.emobility-engineering.com/cell-to-pack-batteries/

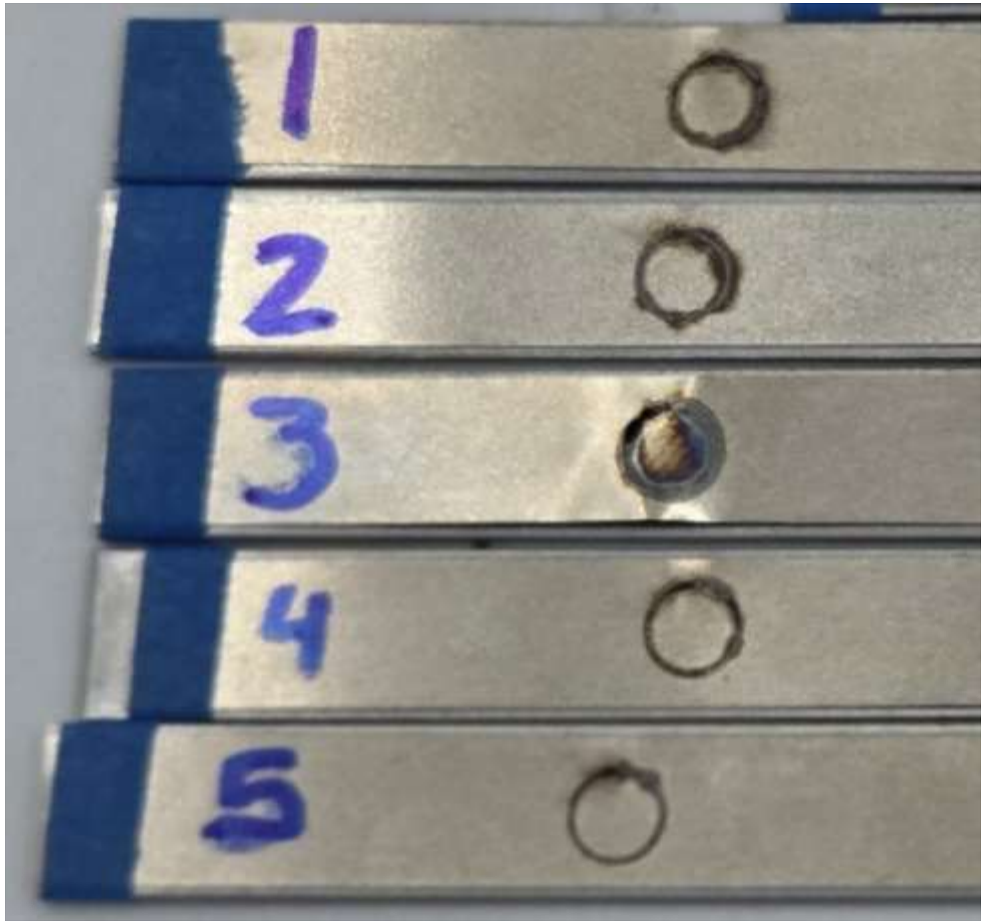
Welding Fixture

- An aluminum breadboard was used to construct a jig to hold each specimen.
- Specimens are held in clamps made from ABS-GF plastic.
- Alignment of specimen is done using an onboard laser.



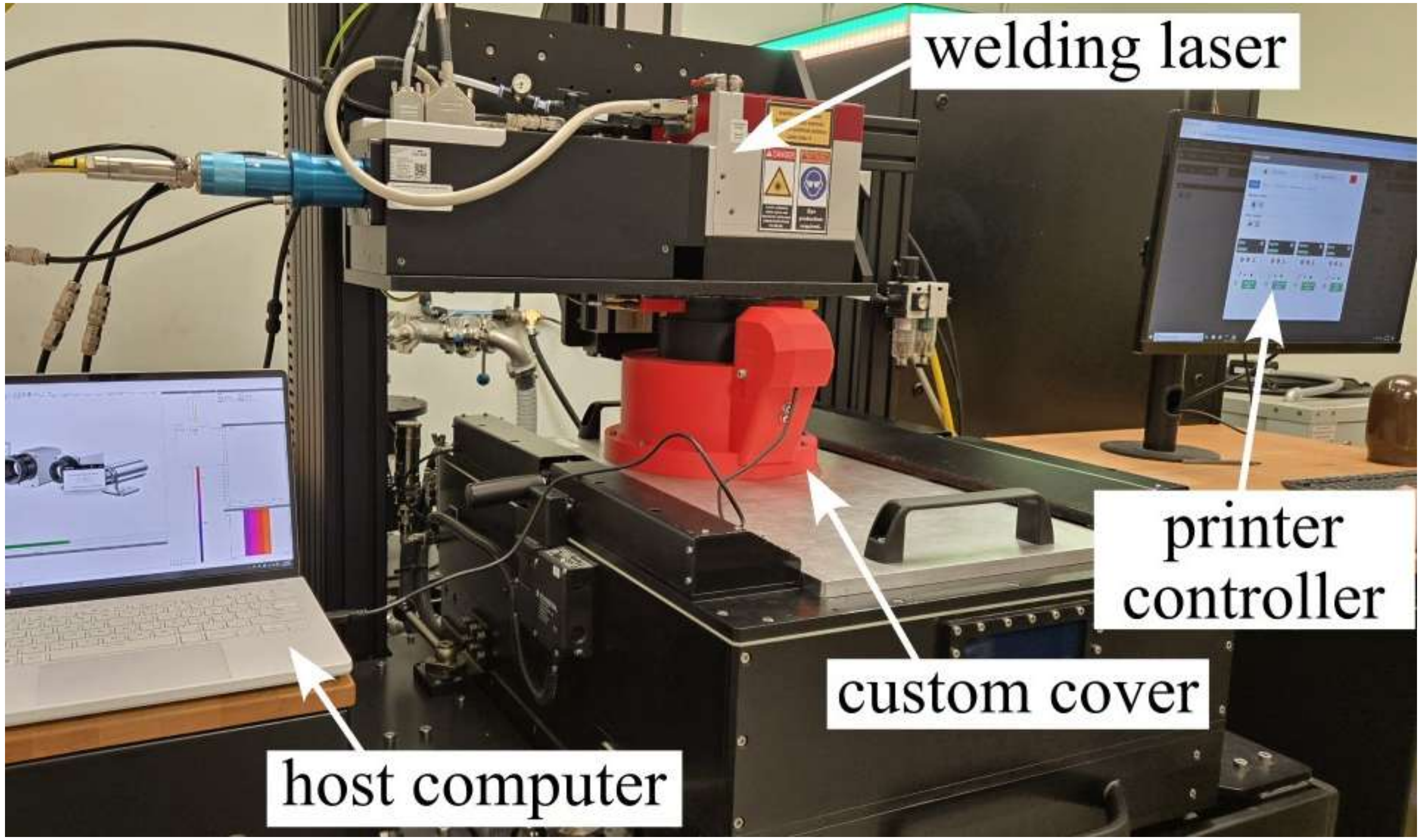
Specimens

- Dissimilar metal weld samples designed to replicate battery tab-to-case joints
- Comprised of:
  - Nickel-plated steel strip (tab material)
  - Stainless steel strip (battery casing surrogate)
- Dimensions:
  - Nickel strip: ~0.15 × 8 × 100 mm
  - Stainless steel: ~0.6 × 9.65 × 85 mm
- Materials chosen to mimic real cylindrical Li-ion battery configurations (e.g., 18650 cells)
- Each specimen was welded using a (~5 mm diameter circular laser pattern



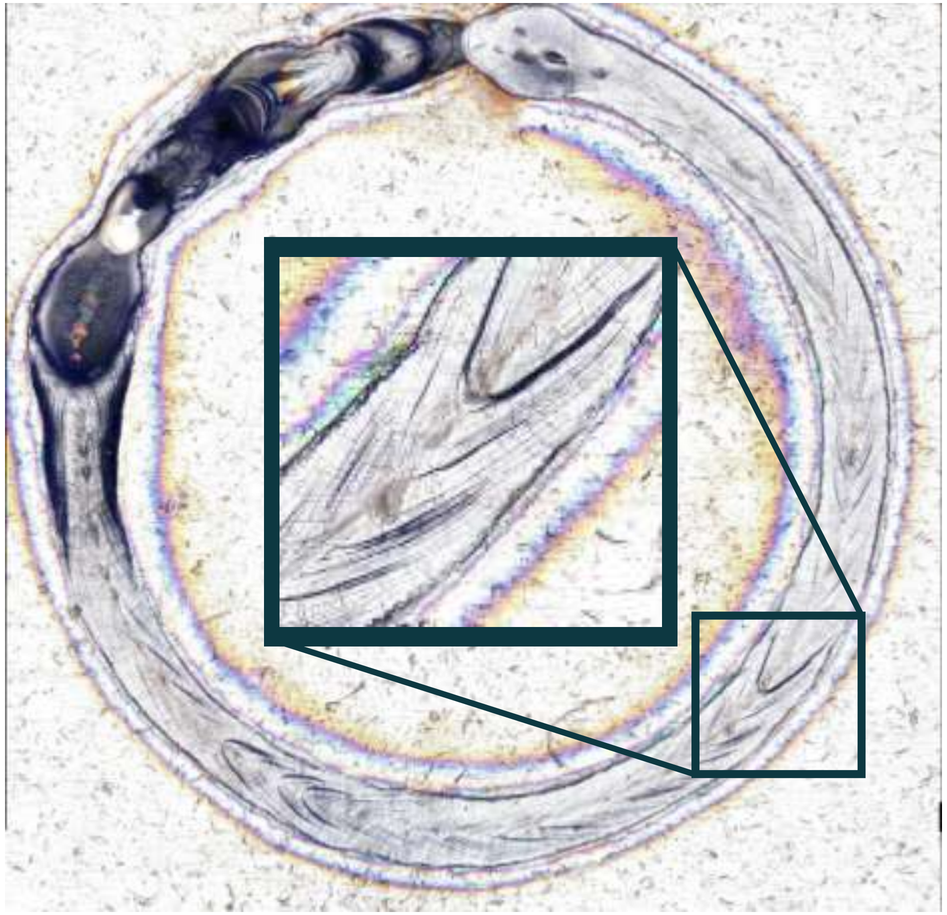
Test Setup

- Utilizing the custom cover equipped with a thermal camera
- No argon used for all experiment runs
- Anti-reflective glass removed to allow collection of accurate thermal data



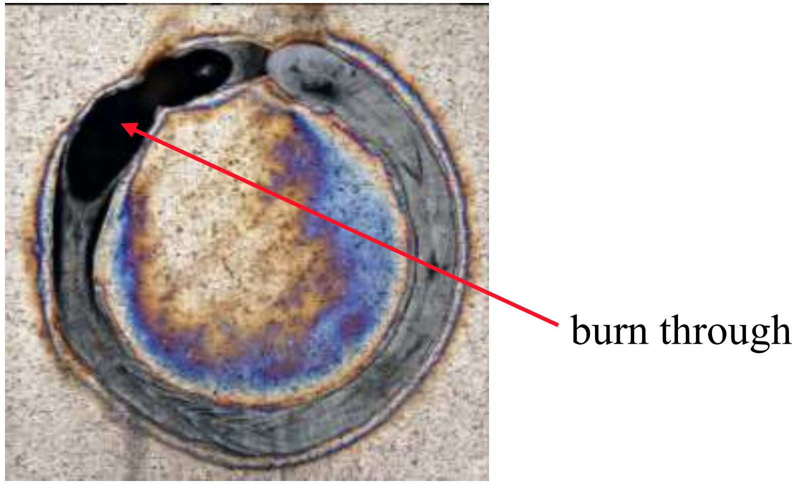
Laser Welding Parameters

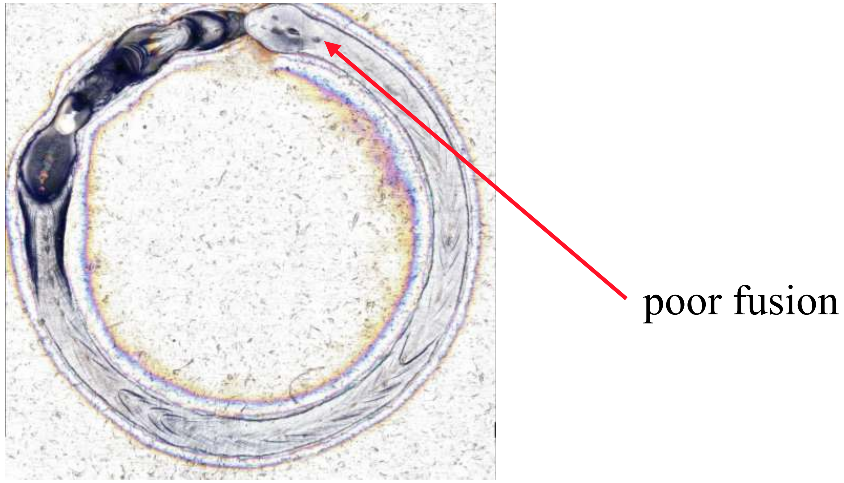
- Laser power held constant at 300 W across all tests
- Welding speed varied (45 → 105 mm/s) to control heat input
- Constant spot size (150 µm) maintained for consistency
- Each condition was tested with replicate samples for comparison



Defects in Battery Tab Manufacturing

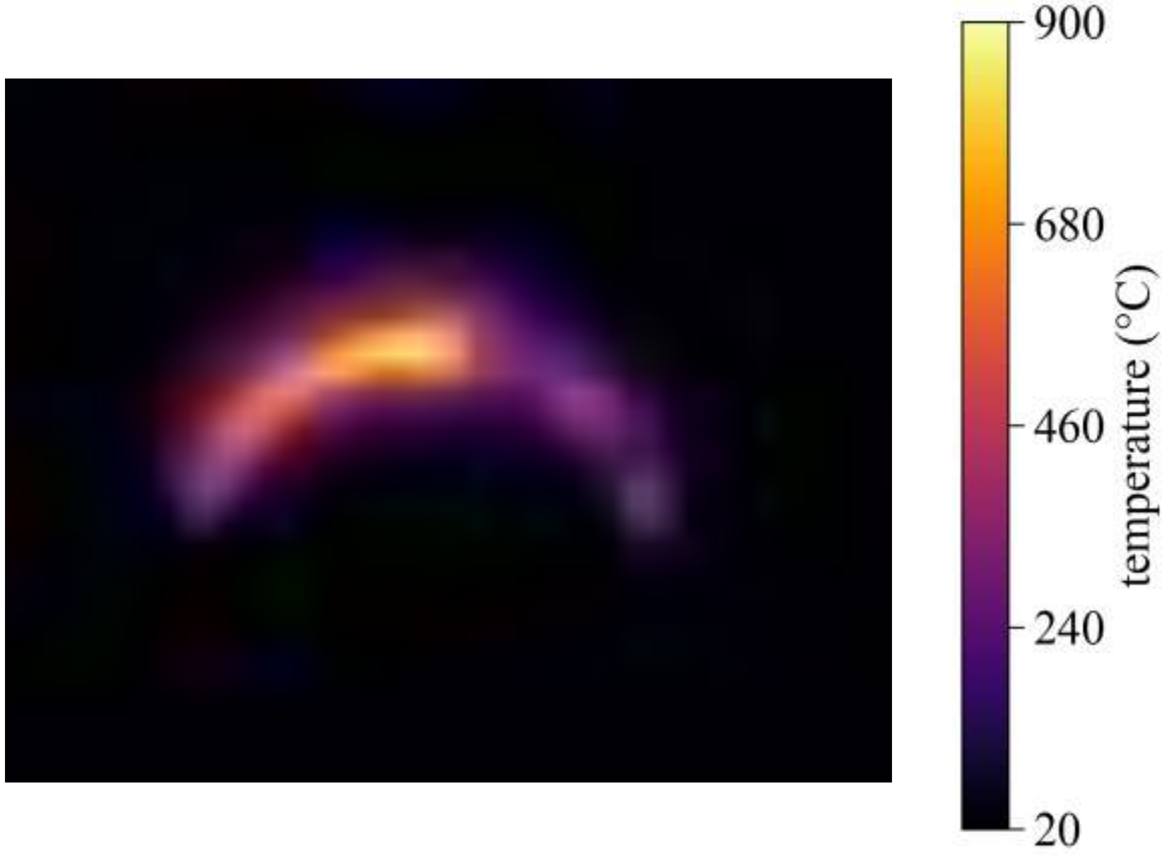
- Process instabilities can produce weld defects
- Common defects include poor fusion and burn-through
- Defects can cause weak joints, increased resistance, and thermal runaway.
- Detection during welding is difficult.





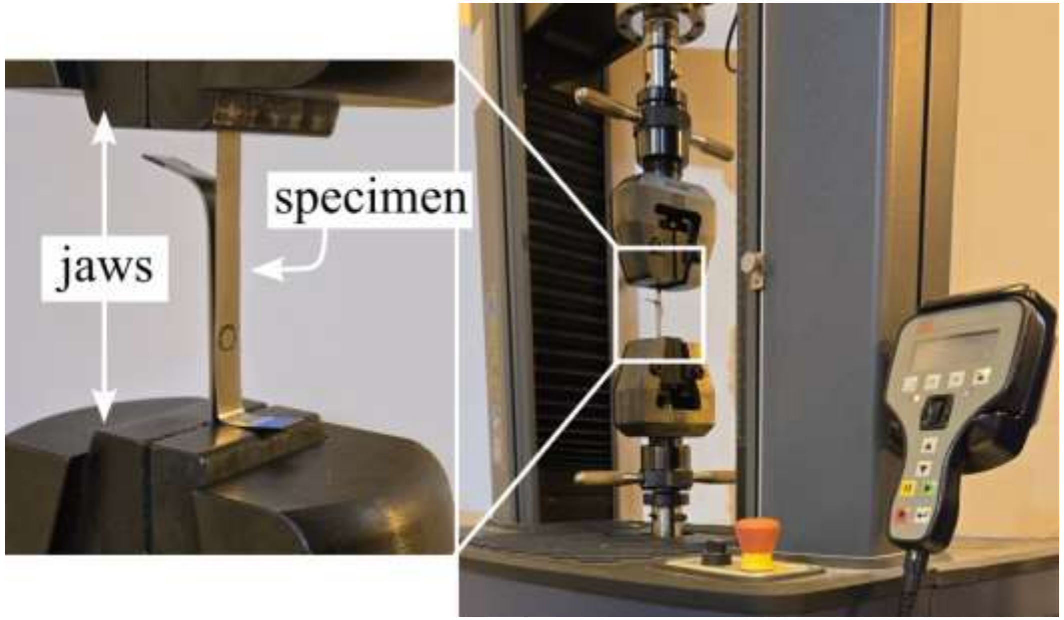
Thermal Imaging

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



Tensile Testing

- Purpose: test weld strength
- Tensile test is qualitative, observing failure mode and location
- Quantitative tensile data not used for this project.



Test	Failure location
1	nickel strip
2	nickel strip
3	n/a
4	nickel strip
5	nickel strip
6	weld
7	nickel strip
8	nickel strip
9	n/a
10	both

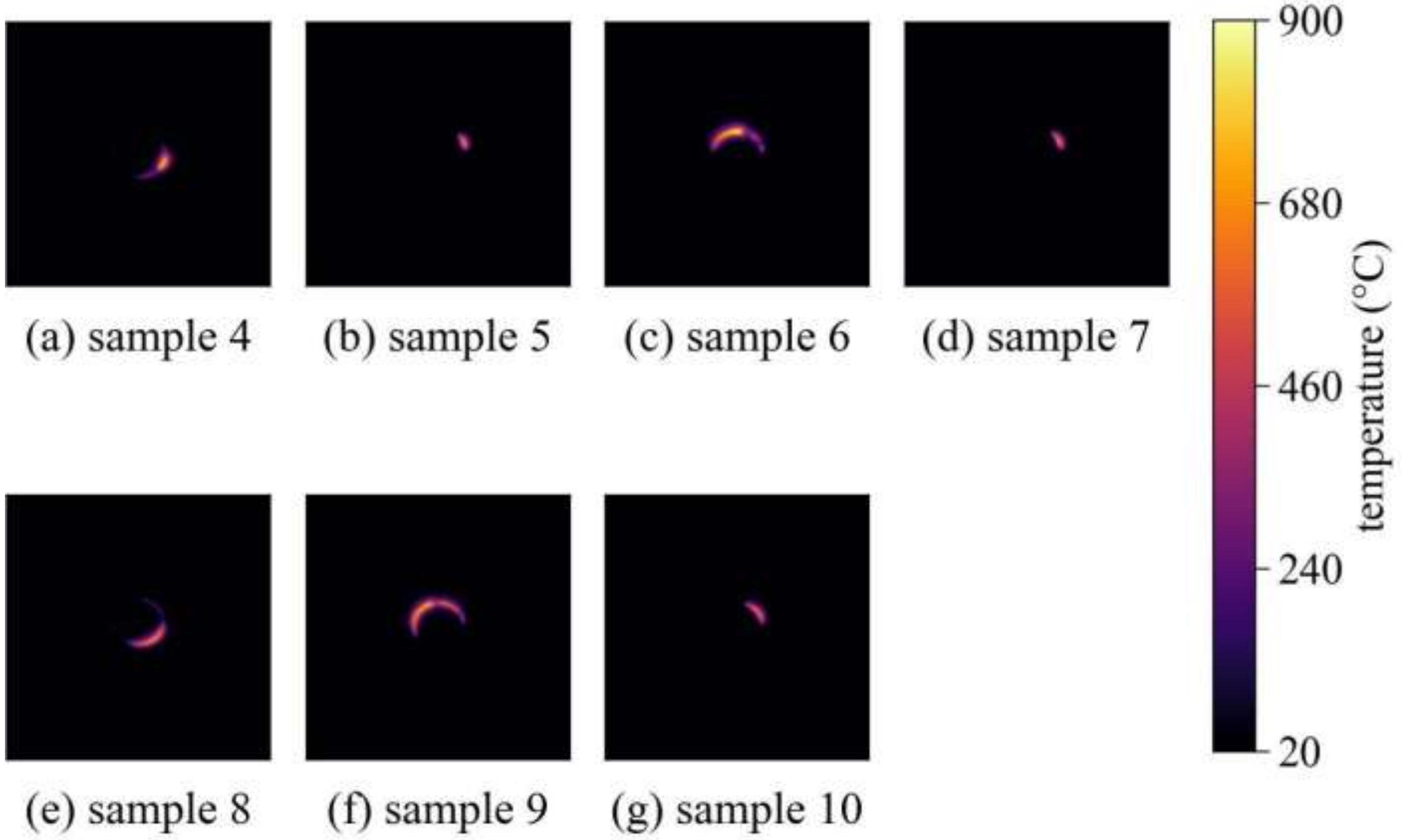
Tensile Data

- Weld results: Around of 70% success rate among samples. Initial quality testing was done using a shim.
- Specimen 16 was not considered for this experiment
- Weld 6 was partially welded but still considered failed.

1	Passed
2	Passed
3	Failed
4	Passed
5	Passed
6	Failed
7	Passed
8	Passed
9	Failed
10	Passed

Feature Extraction from Thermal Images

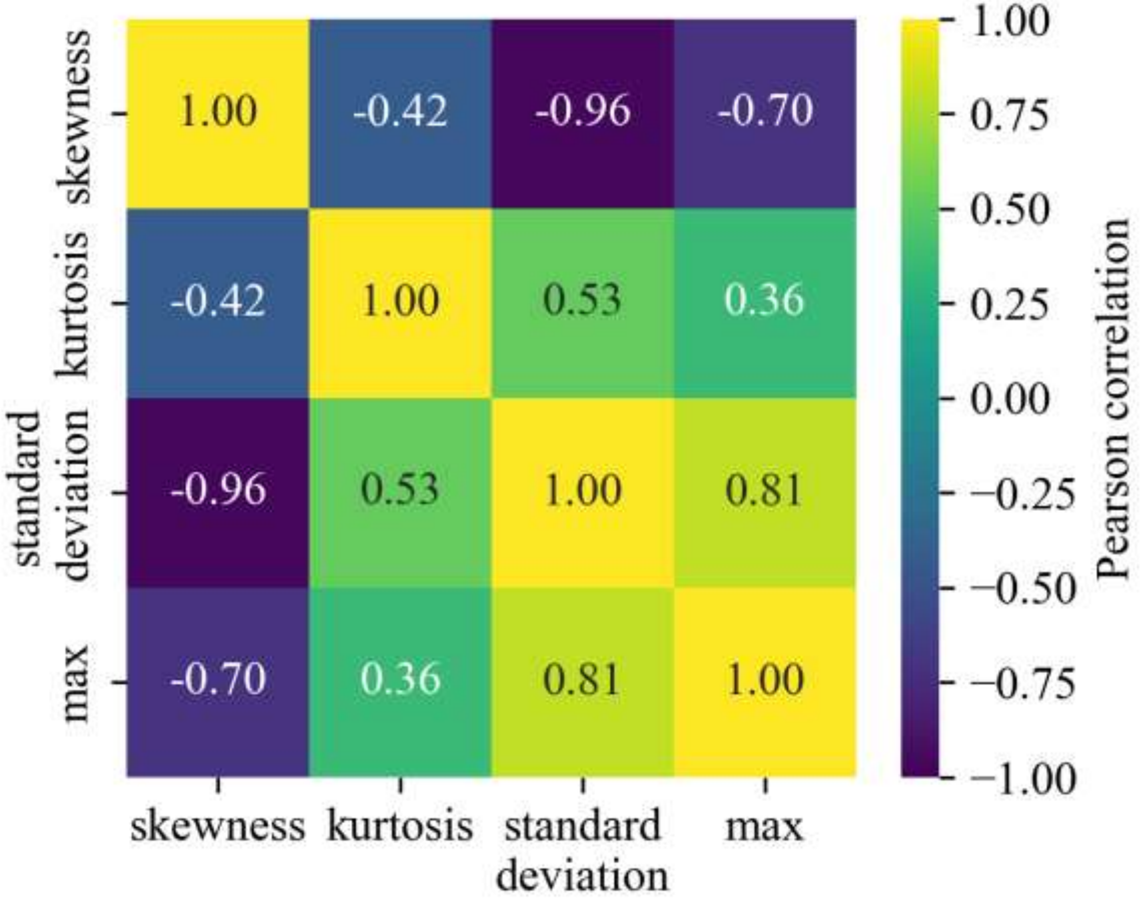
- Region of interest (ROI) isolates the weld zone for consistent analysis
- Extracted statistical features from each image:
  - Maximum temperature (peak intensity)
  - Standard deviation (heat spread/variability)
  - Skewness (asymmetry of heat distribution)
  - Kurtosis (concentration of heat)



(a) sample 4 (b) sample 5 (c) sample 6 (d) sample 7
(e) sample 8 (f) sample 9 (g) sample 10

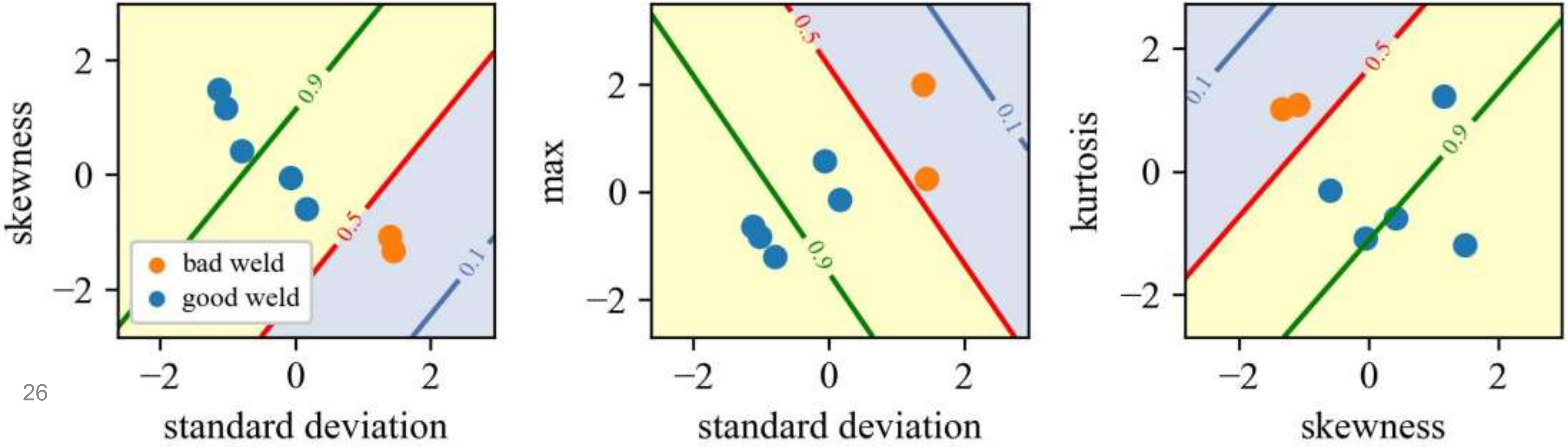
Feature Correlation Analysis

- Correlation matrix shows relationships between selected thermal features
- Strong correlations (e.g., std. dev. vs. max) indicate overlapping information about weld behavior
- Weak correlations highlight complementary features that add unique insight for classification



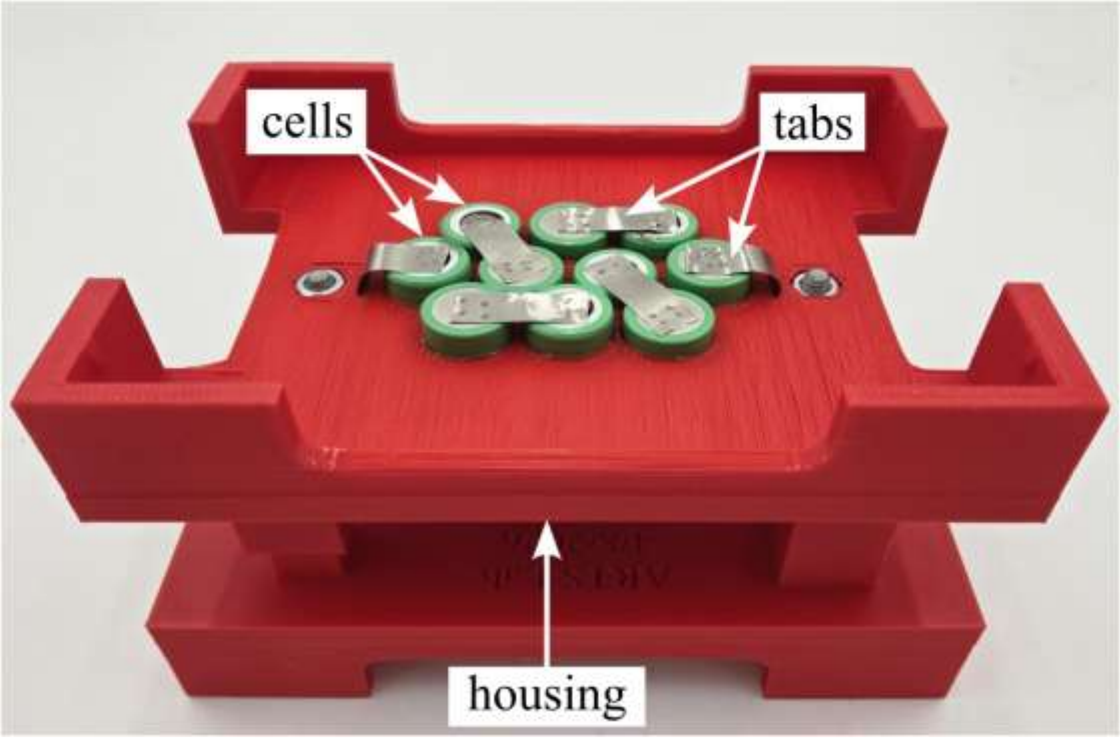
Weld Quality Classification

- Logistic regression applied to thermal features to separate good vs. bad welds using decision boundaries
- Feature pairs (e.g., std. dev., skewness, kurtosis, max temp) show clear class separation and predictive capability



Future Work

- Expand data processing to include both profilometer and quantitative tensile data.
- Develop a "large" dataset of 100 laser battery tabs welds, post-process inspection, and destructive testing.
- Increase the number of samples to improve weld quality classification.



The Open-source Smart Pack for Advanced Research and Control (SPARC) is being developed at USC.

https://github.com/ARTS-Laboratory/Smart-Pack-for-Advanced-Research-and-Control

ACKNOWLEDGEMENT

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Discussion

In Situ Monitoring of Powder Bed Fusion Additive Manufacturing

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

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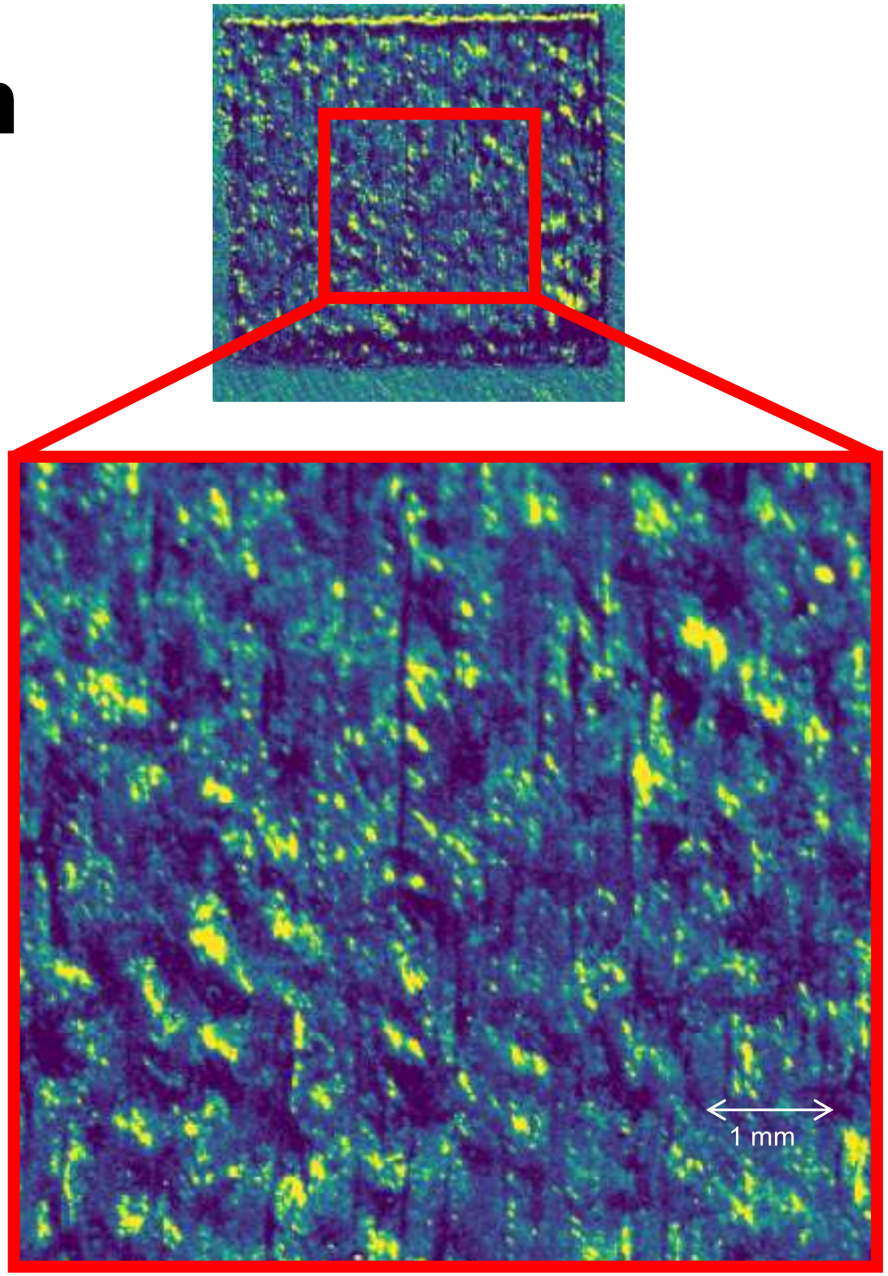
Profilometer Data

- Purpose: Collecting surface roughness data for each sample.
- Images are processed to find height of each pixel
- Data not used for this project

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

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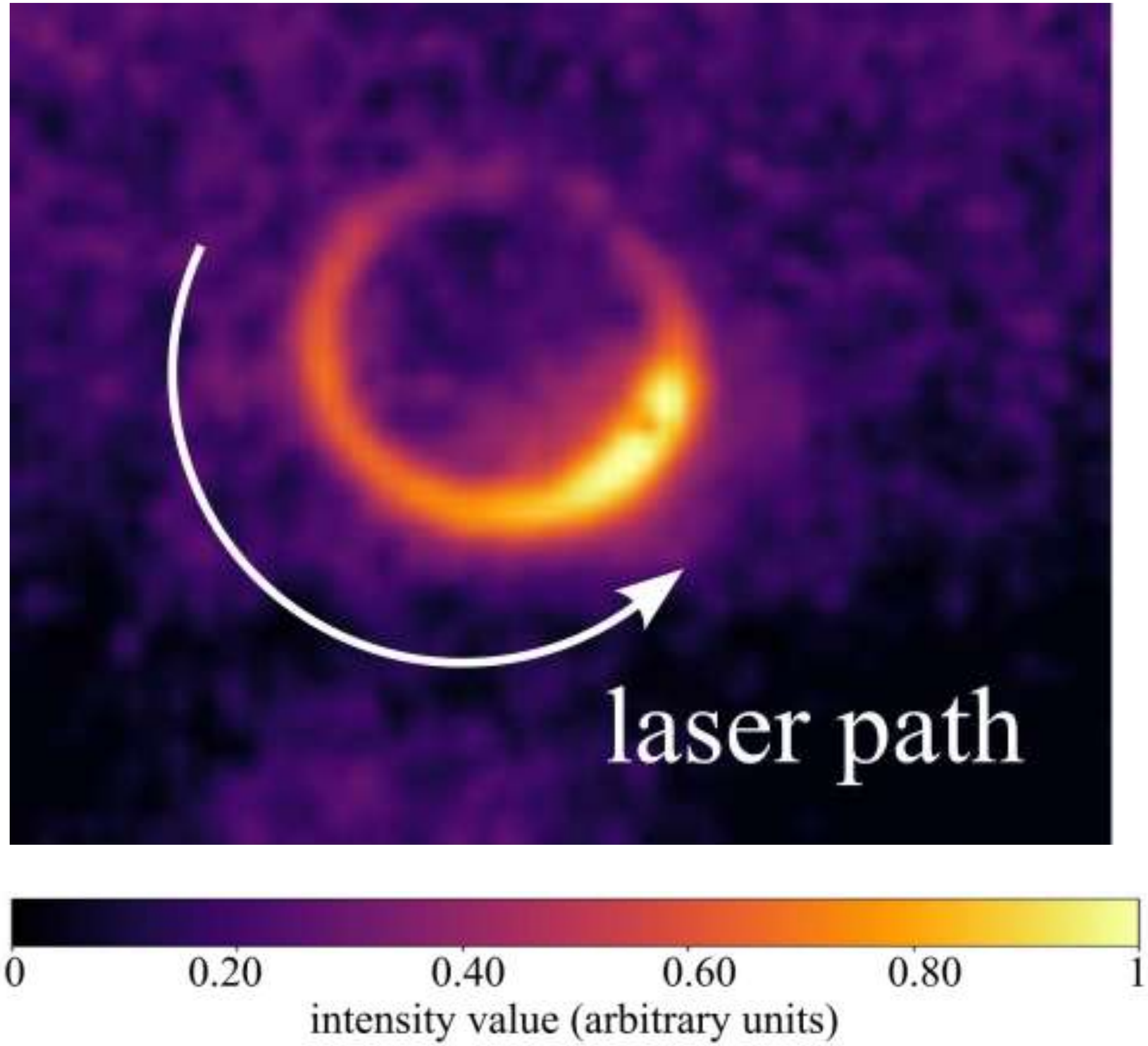
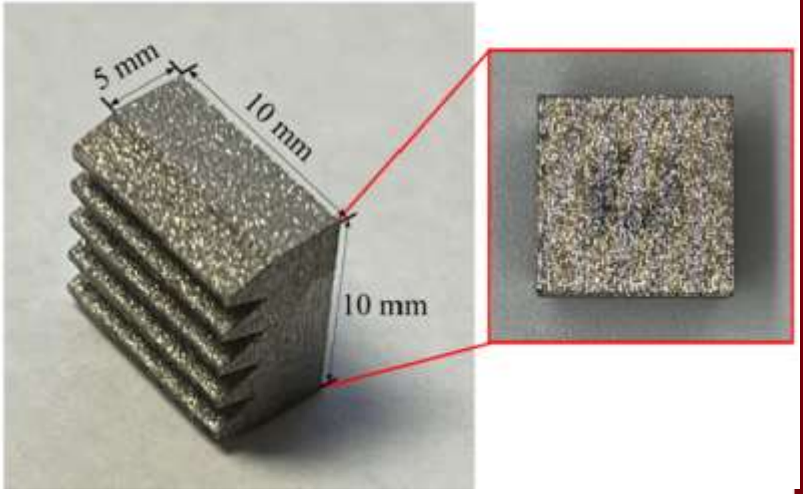
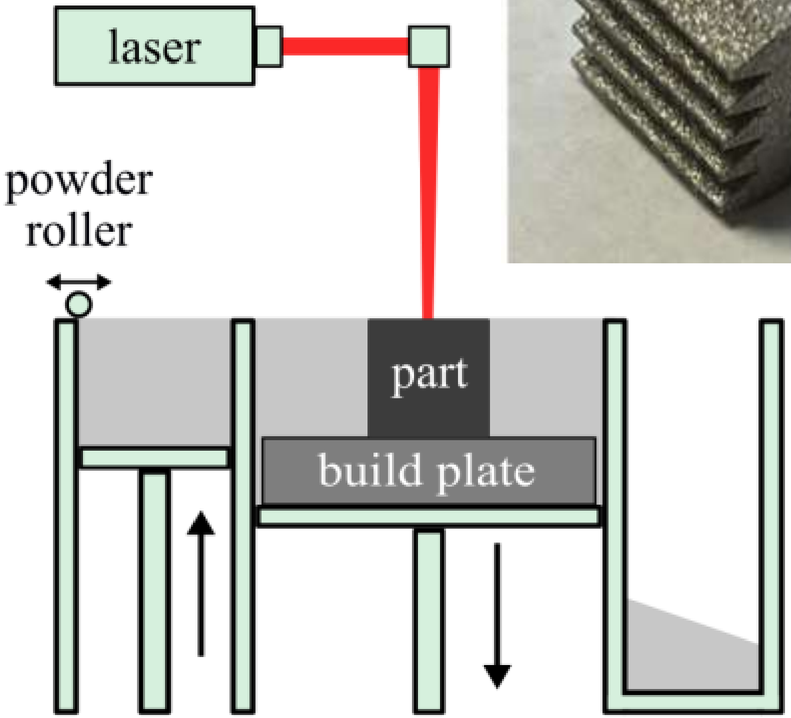


Surface Quality and Melt Pool Behavior

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

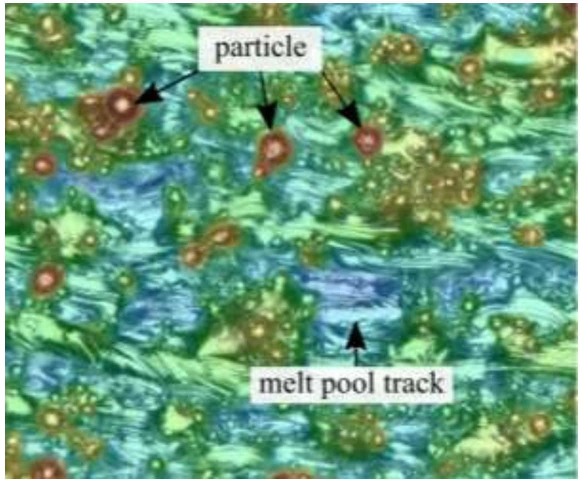




1. https://www.bcn3d.com/introduction-fff-3d-printing-technology-additive-manufacturing-basics/

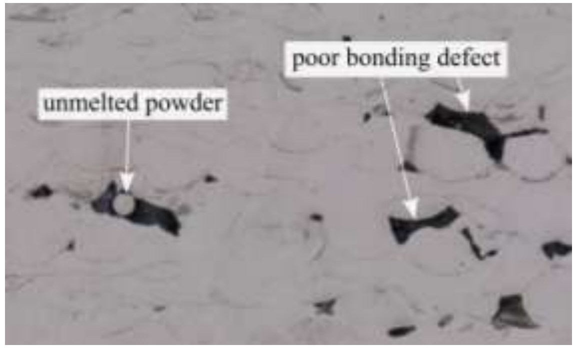
Defects in LPBF Manufacturing

- 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

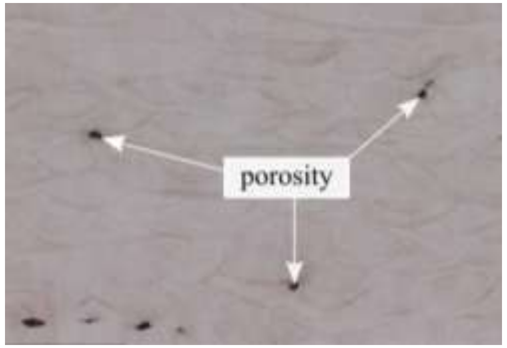


Surface roughness

Distortion



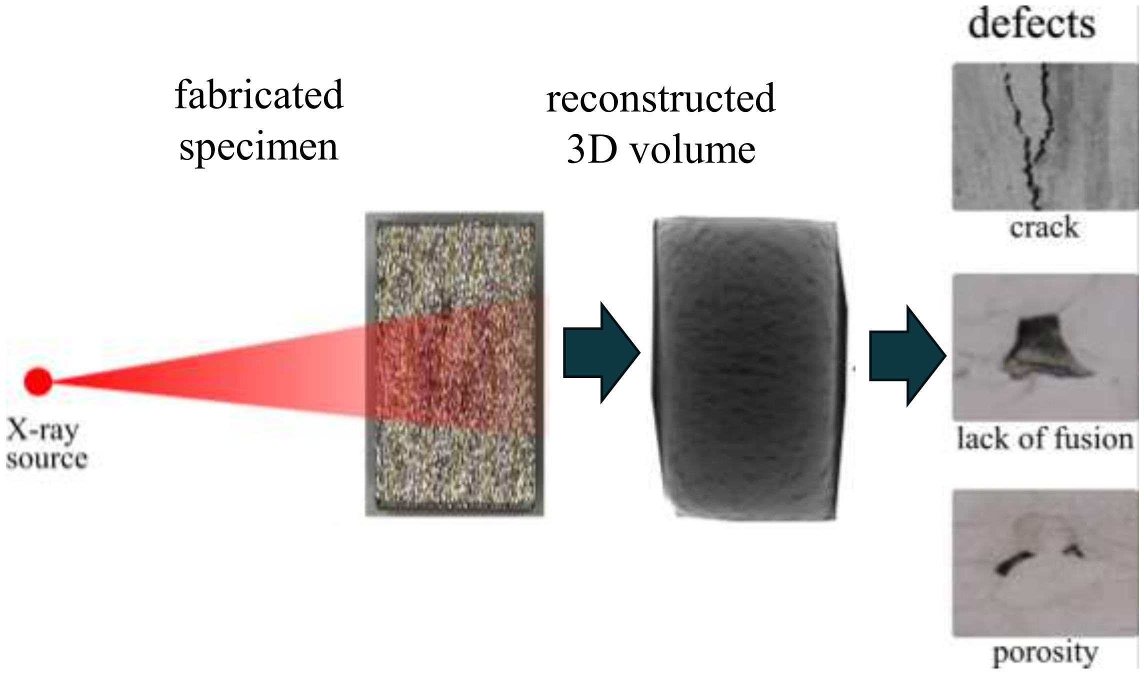
Keyhole



Porosity

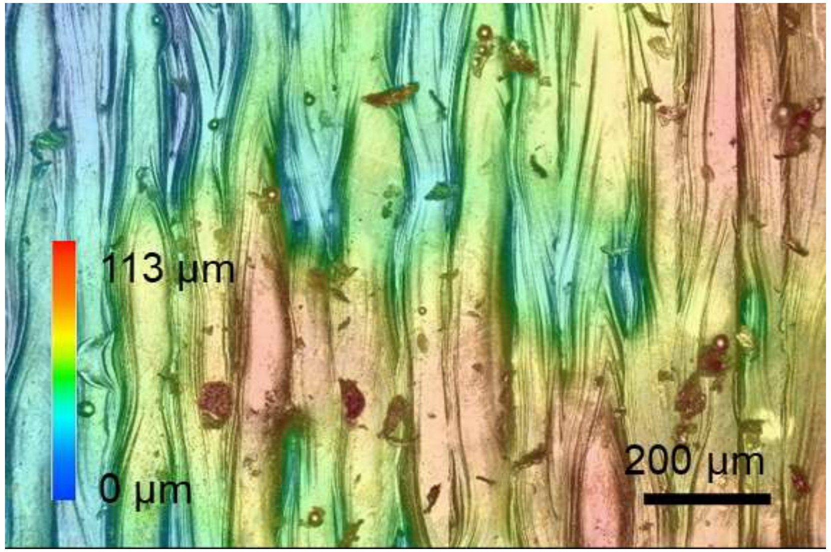
Challenges in LPBF Monitoring

- 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



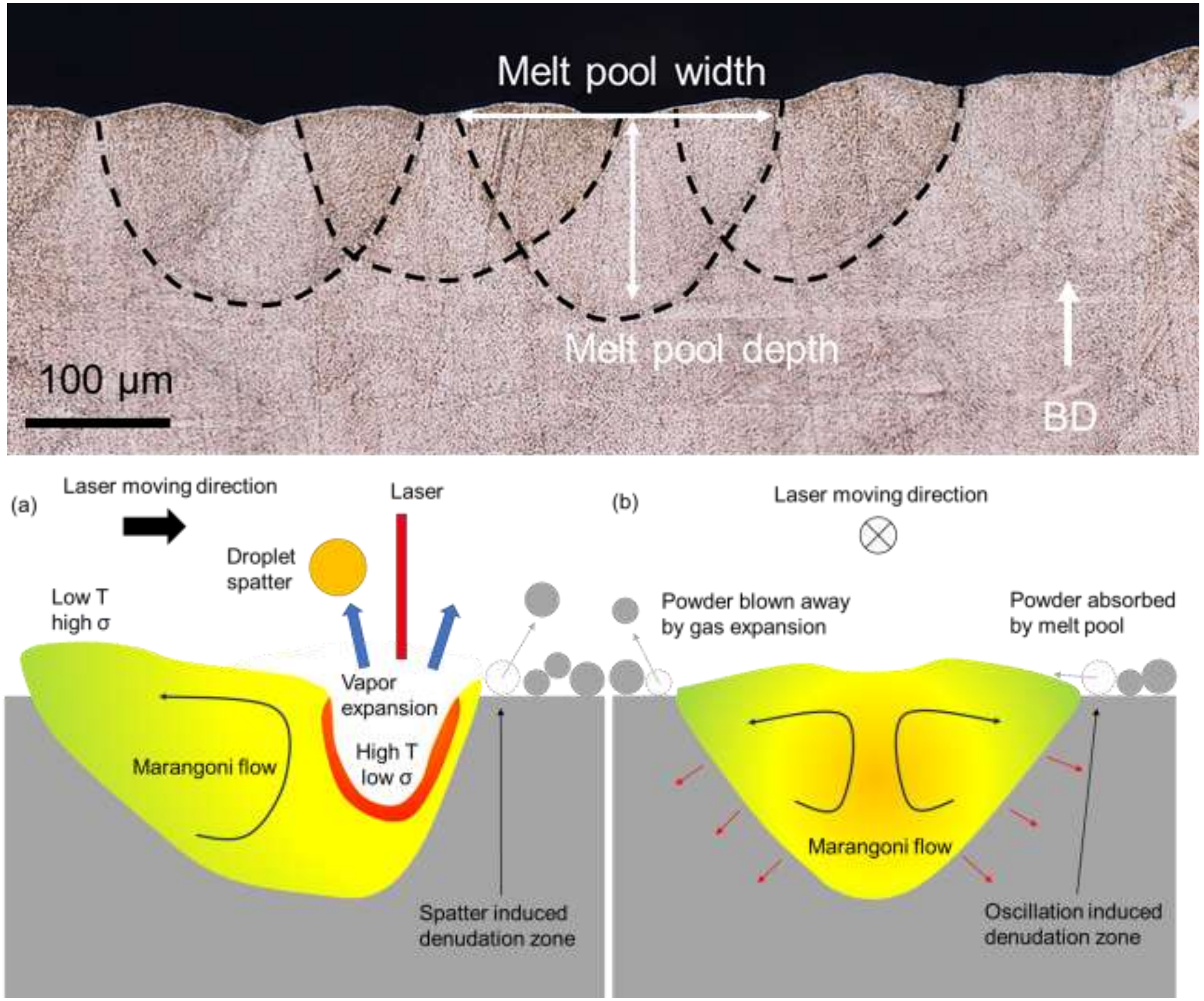
Surface Roughness

- 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



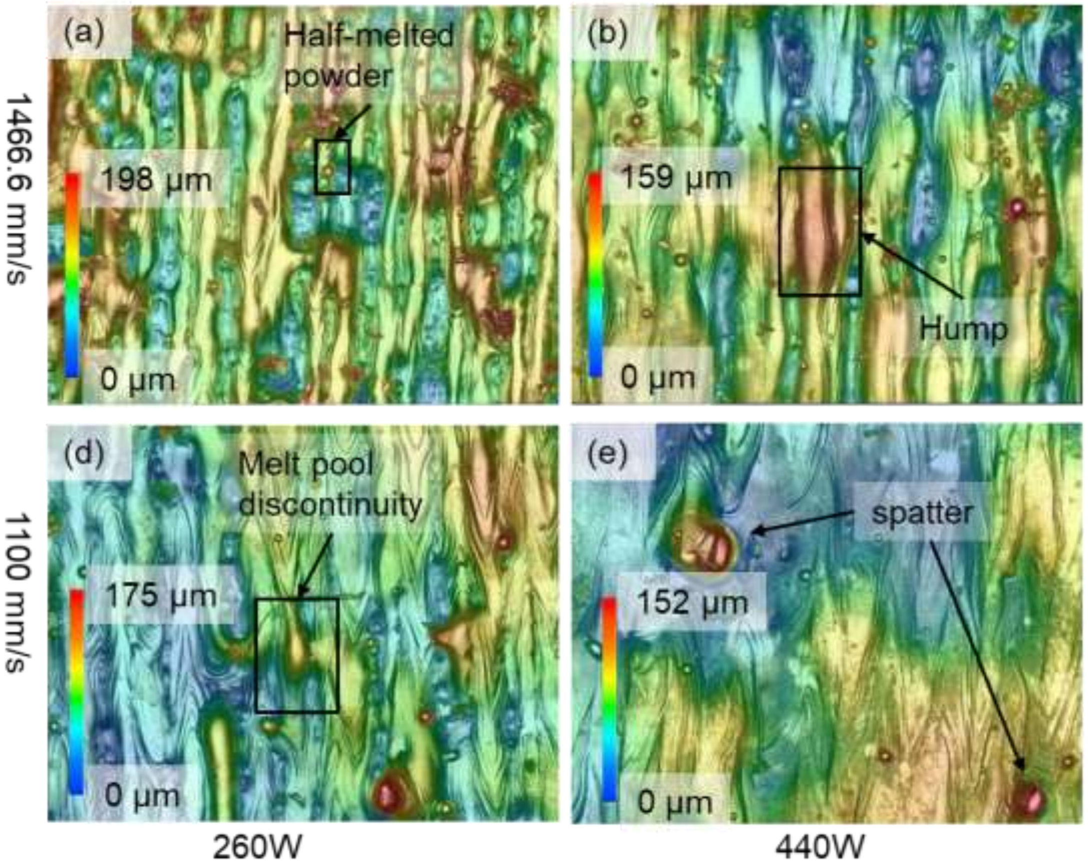
Melt Pool Stability and Spatter

- 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
- Argon was not used during this experiment.