University of Pittsburgh

An Effective Quality Assurance Method for Additively Manufactured Gas Turbine Metallic Components via Machine Learning from In-Situ Monitoring, Part-scale Modeling, and Ex-Situ Characterization Data

Presented to: NETL –UTSR Review Workshop 2021

DOE NETL UTSR Program Award: DE-FE0031774
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Project Objective

- Primary goal: To develop a cost-effective quality assurance (QA) method that can rapidly qualify laser powder bed fusion (LPBF) -processed hot gas path turbine components (HGPTCs) through a machine learning framework, which would assimilate in-situ monitoring and measurement, ex-situ characterization, and simulation data.

- Target application: Use the developed QA tool to qualify advanced HGPTC produced by LPBF in Inconel 718.

Project Structure - Research Tasks and Organization

An Effective Quality Assurance Method for Additively Manufactured Gas Turbine Metallic Components via Machine Learning from In-Situ Monitoring, Part-scale Modeling, and Ex-Situ Characterization Data

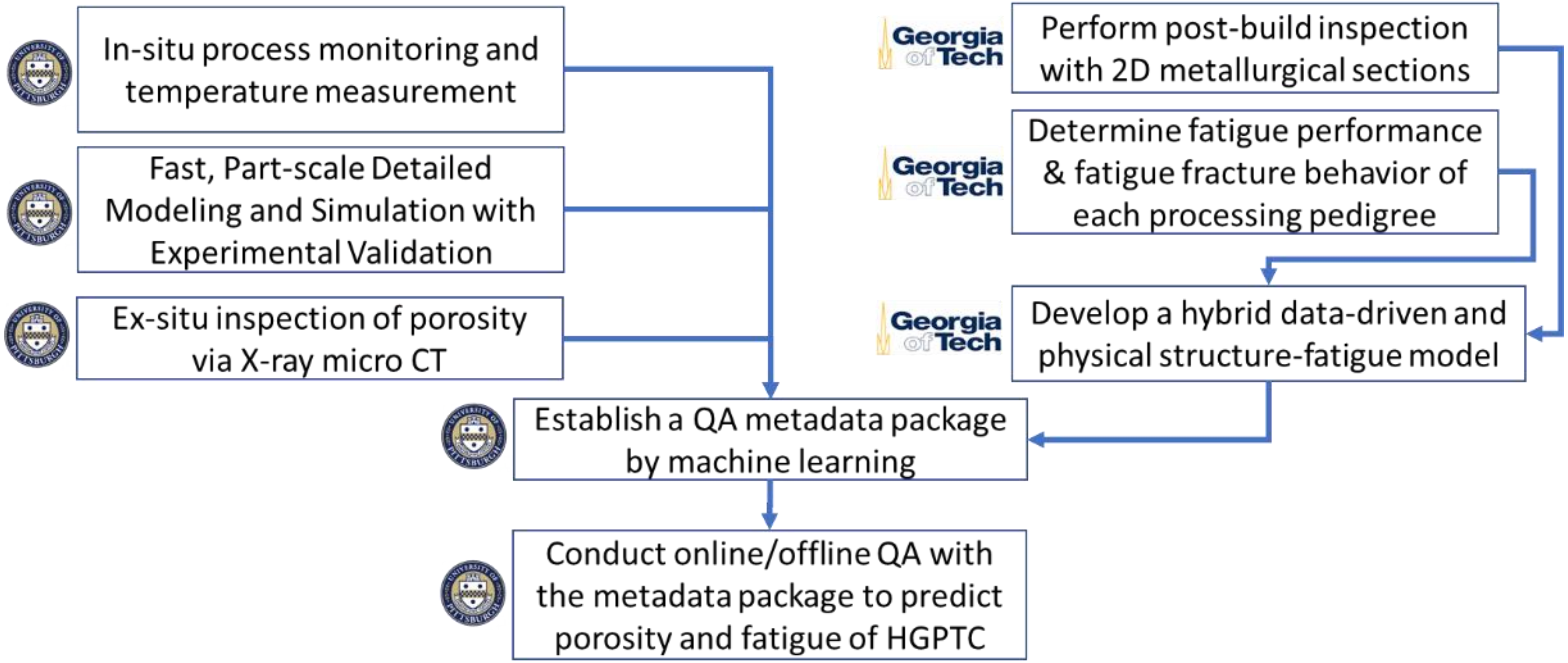
University of Pittsburgh

Georgia Institute of Technology

Turbine Manufacturer

ANSYS

Research Task Plan (3 years)



Progress Review for Q1-Q8 (10/01/2019 – 09/30/2021)

PI Zhao

❖Task 2.1 Develop an in-situ monitoring and measurement system which consists of the following two subsystems

➢ **Task 2.1.1**: In-situ meltpool (MP) temperature monitoring & measurement

- ✓ **1. Developed and validated meltpool temperature**
- ✓ **2. Completed big data analytics for monitoring the printing of five fatigue bars. Fatigue testing (Co-PI Neu) of the five bars will provide a reference for testing the upcoming printed turbine blade coupons.**

➢ **Task 2.1.2**: Develop an in-situ off-axis layer monitoring system

- ✓ **Algorithms for registering MP locations using off-axis and on-axis camera have been developed.**
- ❑ **Need to correlate the derived spatial profiles of meltpool signatures to ex-situ characterized layer-specific anomalies.**

Progress Review for Q1-Q8: 10/01/2019 – 09/30/2021)

PI Zhao

❖Task 2.4 Establish a QA metadata package by machine learning of simulation and in-situ/ex-situ data

➢**Task 2.4.1**: Build a database to log and consolidate multi-source data

- ✓ **Set up a NAS (network-attached storage) system for the project data storage, sharing and analytics.**
- ✓ **Installed the NIST AMMD software on our lab computer**

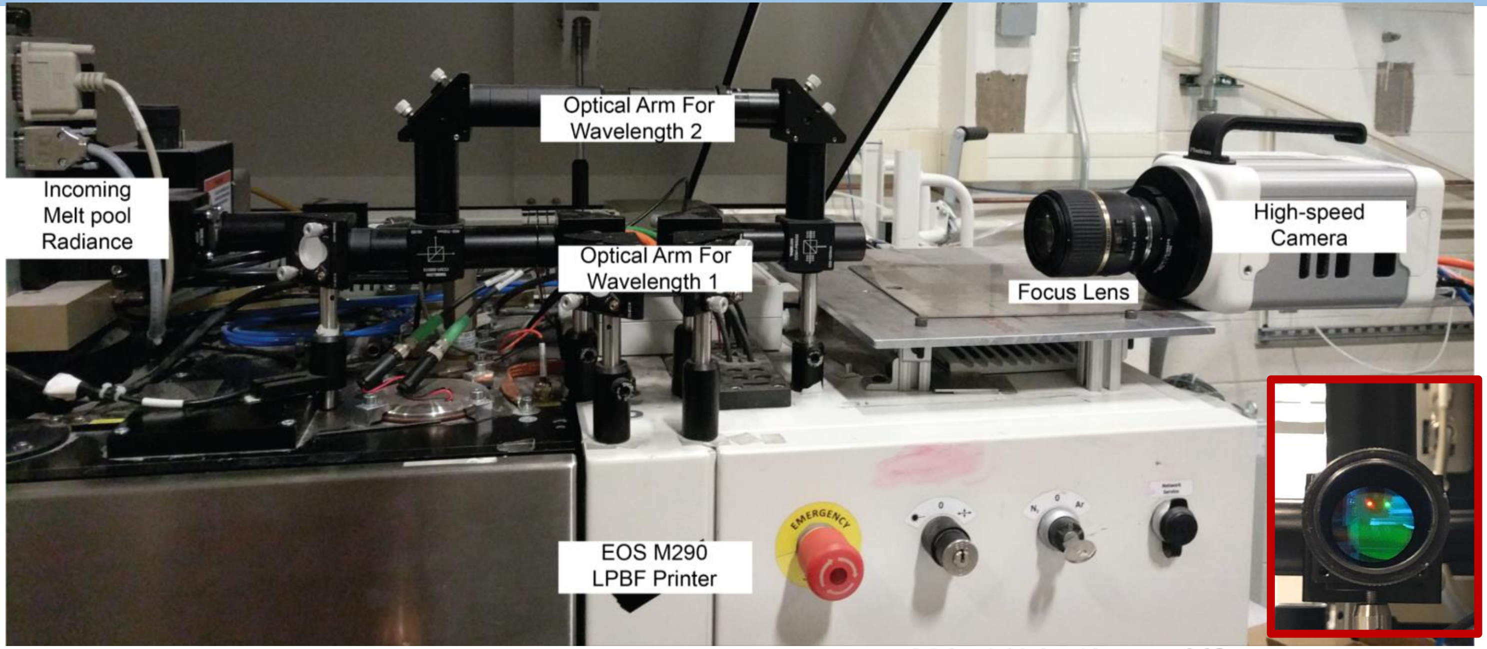
➢**Task 2.4.2**: Develop machine leaning algorithms to establish correlations of process-structure-properties

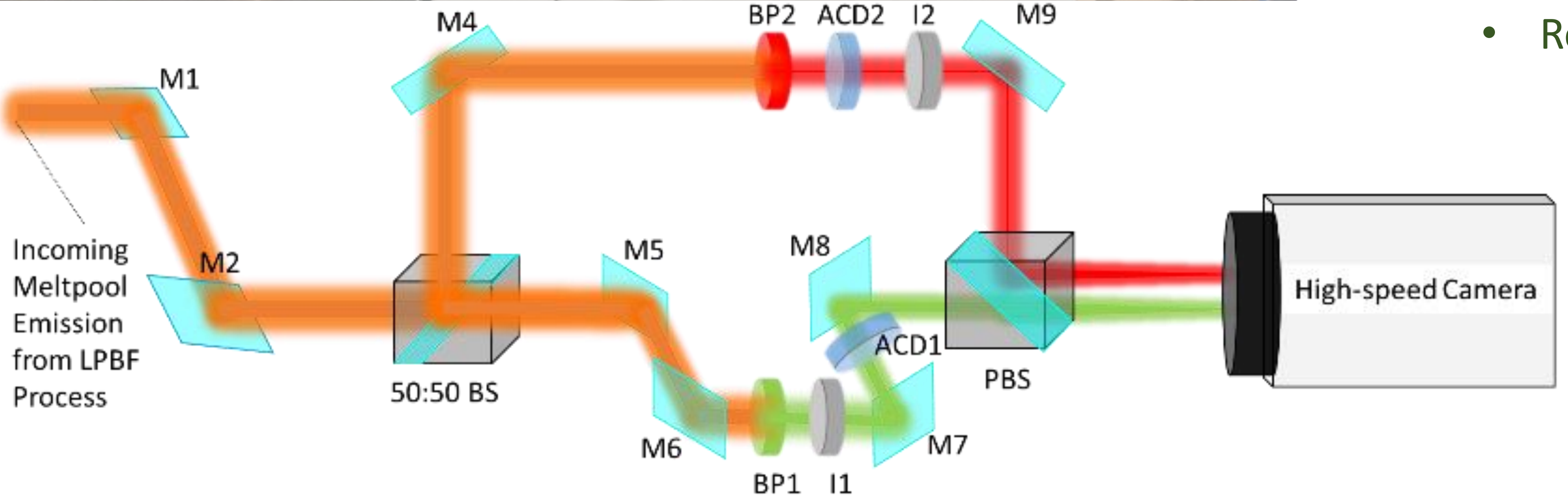
- ✓ **Supplement data computing resource granted (data storage, GPU and AI-GPU allocations) by XSEDE**
- ✓ **Received NSF XSEDE's data & computing resource allocations on Pittsburgh Supercomputing Center Bridges-2 via two grants (XSEDE Awards: MCH200015 & MCH210015) , paving the way for our data processing and machine learning tasks**
- ❑ **Transfer and store all-hands data on PSC Bridges-2 Platform**
- ❑ **Develop machine learning algorithms to analyze process-structure-property relationship**

STWIP (Single-camera Two-Wavelength Imaging Pyrometry): Objectives

- Develop a **cost and data effective, compact** **Single-camera two-wavelength imaging pyrometry (STWIP)** method as opposed to a traditional Two-camera system.
- Develop a **continuous** **melt pool monitoring system** for practical printing scenarios
- Develop a **robust and modular** monitoring system and methodology for specifically **monitoring the melt pool temperature and morphology**
- Provide the AM community with the **extensive** **datasets for LPBF based metal AM** and help develop an **integrated** **machine learning framework for correlating melt Pool and part properties**

STWIP (Single-camera Two-Wavelength Imaging Pyrometry): System Setup





M 1-9: Mirrors 1 to 9; 50:50 BS: 50:50 Beamsplitter; BP1: Beam pass Filter #1 (550nm); BP2: Beam pass Filter #2 (620nm); ACD 1-2: Achromatic Doublets; I1-2: Irises; PBS: Polarizing Beamsplitter.

System Specifications and Merits:

- Installed on EOS M290 DMLS printer
- System working wavelengths: 550nm (λ_1) and 620nm (λ_2)
- Single high-speed camera
  - Photron Nova S12 with a sensor resolution 20 µm/pixel
  - Framerates capability: >100,000 fps
- Continuous monitoring of up to 50 layers for real-world test samples at 30,000 fps
- Resulting MP metrics:
  1) MP Intensity
  2) MP Temperature
  3) MP Morphology (Area and Shape)
  4) MP Shifting on Sensing Plane

STWIP for in-situ Meltpool Temperature Measurement: Validated Performance

Our STWIP Measurement Performance

- **Accuracy:**
  >90% for all the tested cases, projected to be >95% for a real test case

- **Repeatability:**
  >95% for all the tested cases, projected to be >98% for a real test case

- **Uncertainty:**
  The relative uncertainty in temperature evaluated from our system is < 2.801%, which is the **maximum relative uncertainty** of the system evaluated at I_{12} = 2 (**very uncommon in typical print scenarios**).

Remarks / Recommendations

- STWIP temperature measurement performance significantly depends on the following factors **to obtain intensity values and intensity ratios with desired accuracy and precision**.
  - The two-wavelength MP image acquisition (e.g., well-aligned optical setup, proper spectral sensitivity of camera)
  - The image transformation also plays a crucial role in accurately evaluating the intensity ratio.

- **The temperature uncertainty U_T decreases as A_{12} increases, indicating a direction of improvement to design a favorable optics system with higher A_{12}.**

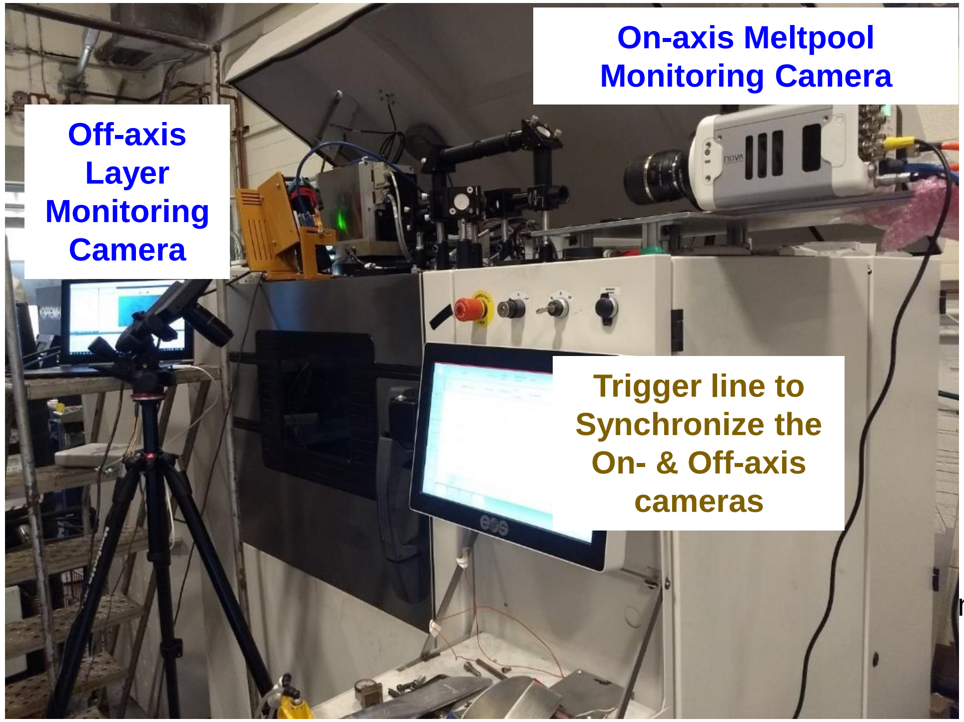
- **STWIP is likely to possess even better measurement capability** given a more capable validation approach and experimental setup that can overcome the EOS machine constraints

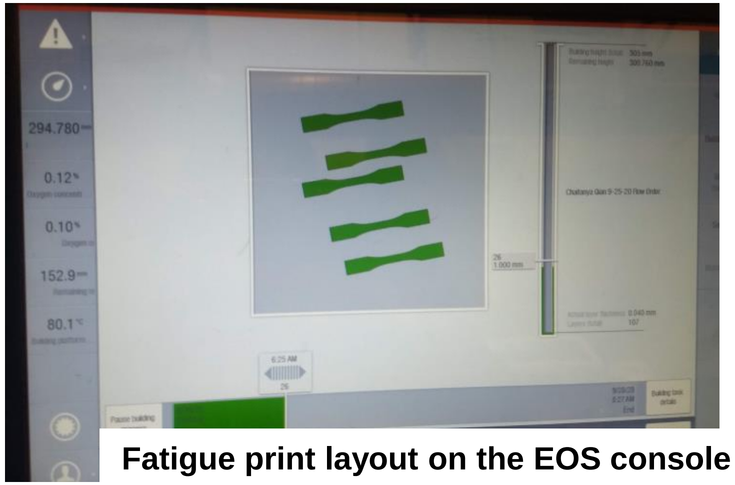
STWIP Application Demo: Monitor Meltpool during LPBF of 5 Fatigue Specimens

Multiple sets of experiment were conducted.

E.g., in one experiment as shown, a complete build of five fatigue bar samples designed per ASTM standards

- **<u>Data Acquisition and Storage</u>**: Each fatigue bar print time is approximately 14.4 s and each fatigue bar print is separated by 0.3s. Each printed layer's video data is divided into five segments of each fatigue bar's meltpool image data.
- **<u>Data Processing and Analytics</u>**: The data processing is in progress. From the intensity monitoring of each layer, we will extract all the key features including each meltpool's temperature profile, size, shape, and location, as well as hatching pattern for each print layer.



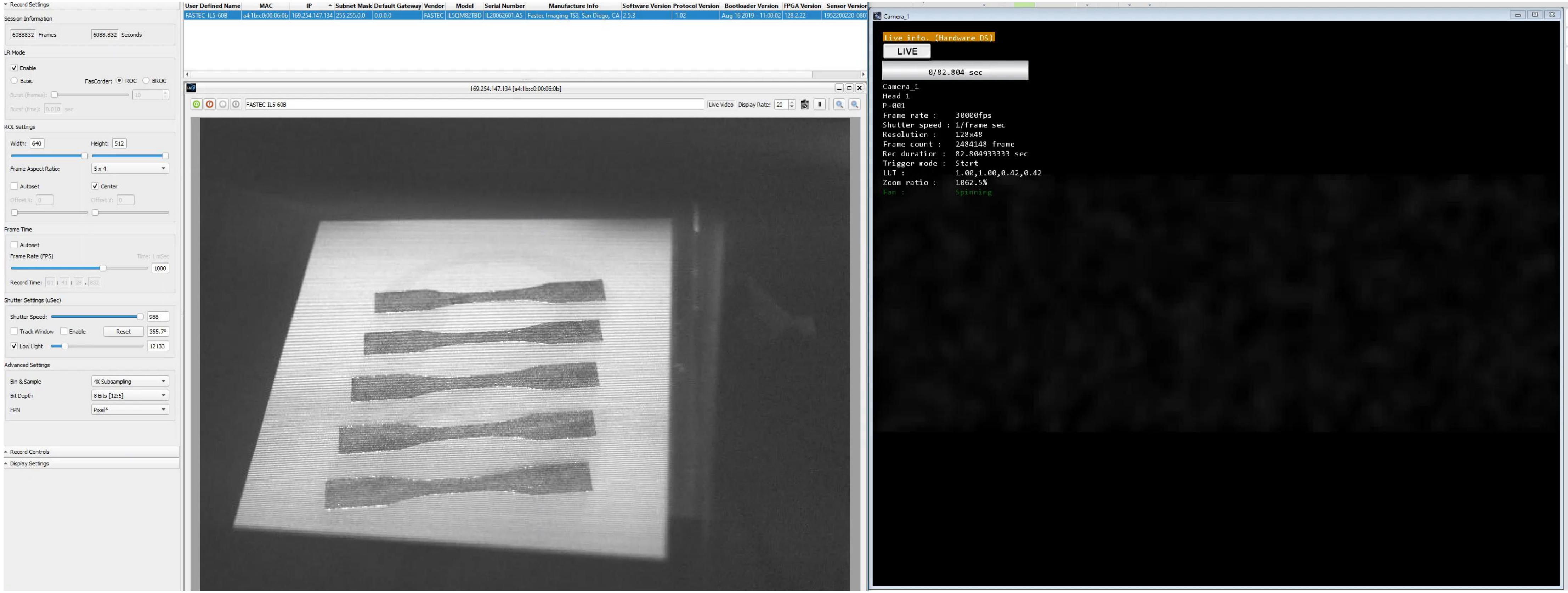

Fatigue print layout on the EOS console


Snapshot of the fatigue bar print


Printed fatigue bar samples (numbered)

STWIP Application Demo: Monitor Meltpool during LPBF of 5 Fatigue Specimens

- We completed a batch of five fatigue bars on 12/17/2020. Both on-axis and off-axis data for this print was collected
- The print parameters were: Laser power 285W, Scan speed 960 mm/s.
- Off-axis data was acquired at 1000fps and on-axis data was acquired at 30,000fps at 128x48px resolution



STWIP Application Demo: Monitor Meltpool during LPBF of 5 Fatigue Specimens

Data Analysis:

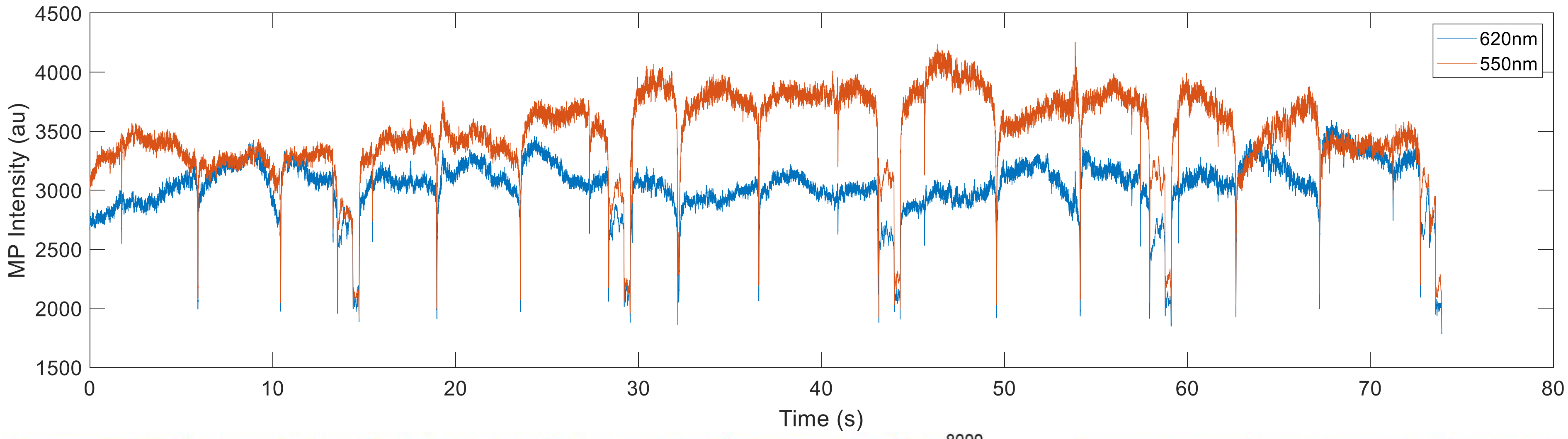
For the first time we demonstrated a large-scale continuous data monitoring for up to **50 print layers**.

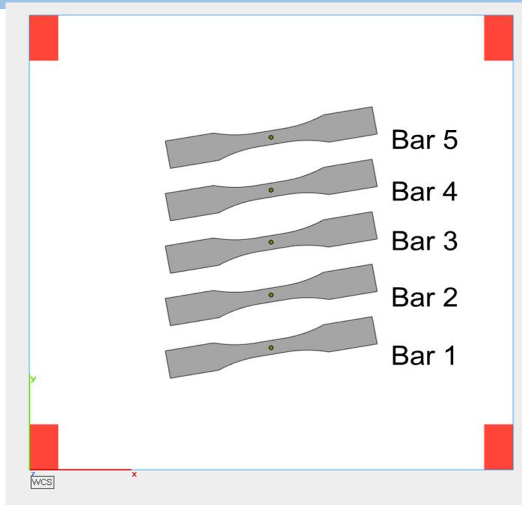
Each print layer elapsed 72 seconds with approximately **2.2 million images in each layer**. **Over 1 billion images were monitored and processed**.

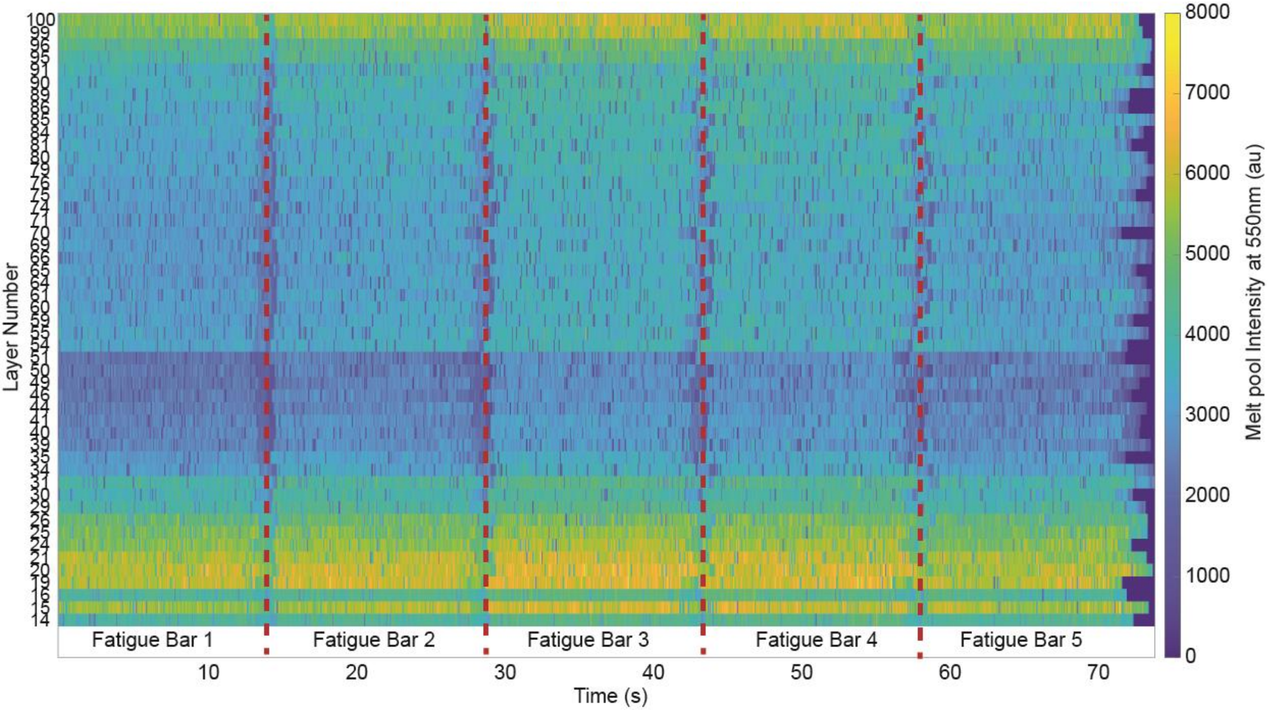
Results: The **melt pool (MP) metrics** obtained from this monitoring are

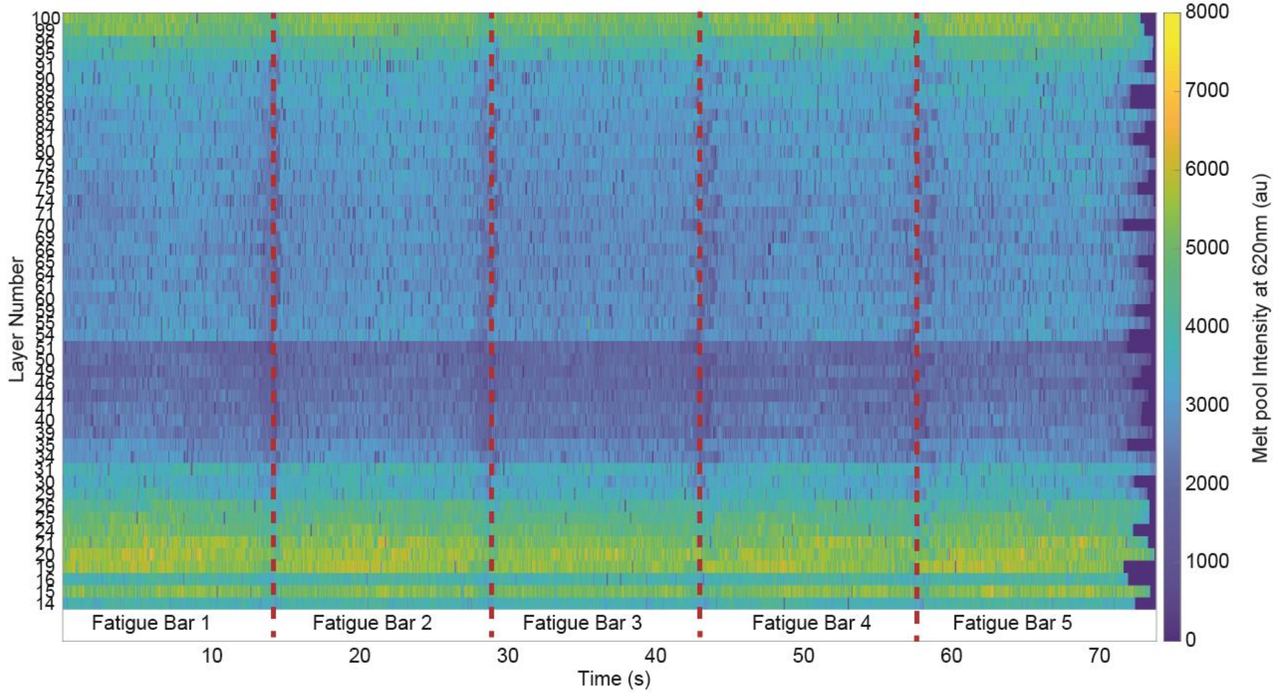
- **MP intensity**
- **MP average temperature**
- **MP temperature profile**
- **MP area**
- **MP shape (ellipticity)**
- **MP relative location shifting on sensing plane**

STWIP Application Demo: Result #1: Two-wavelength Melt Pool Intensity Profile



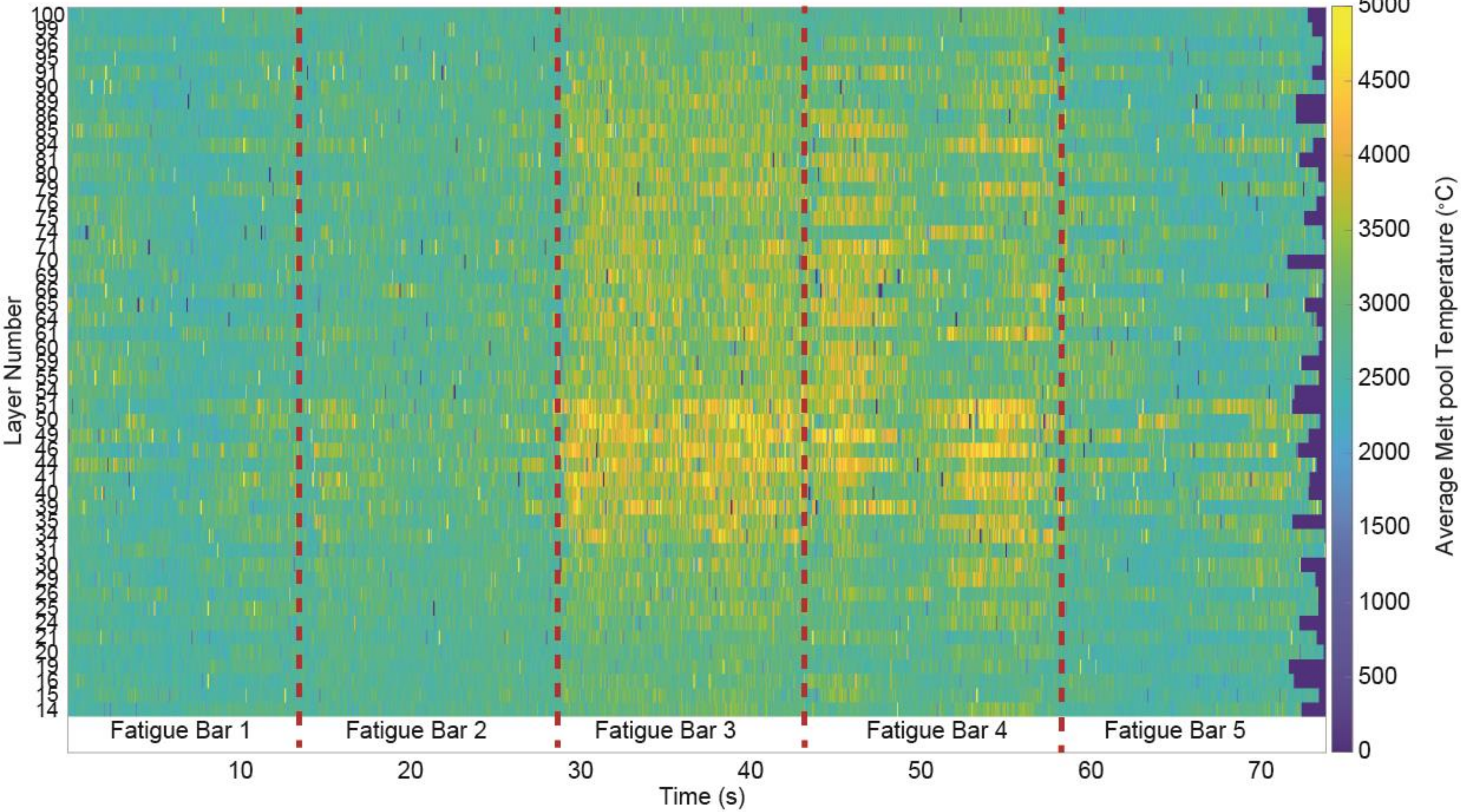


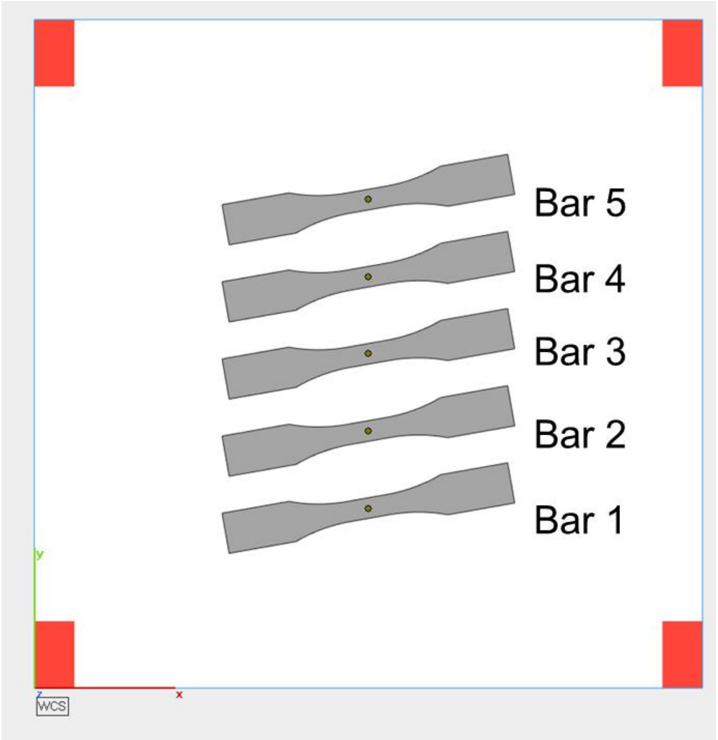




STWIP Application Demo: Result #2: Average MP Temperature

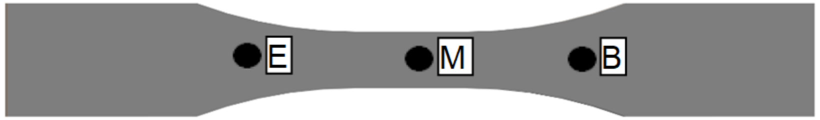
Average MP temperature of the five printed Fatigue Bars corresponding to 49 layers, derived from the MP intensity profiles acquired at the two working wavelengths of the in-situ system (550 nm and 620 nm). The red dashed lines show the approximate temporal boundaries of each printed Fatigue Bar.



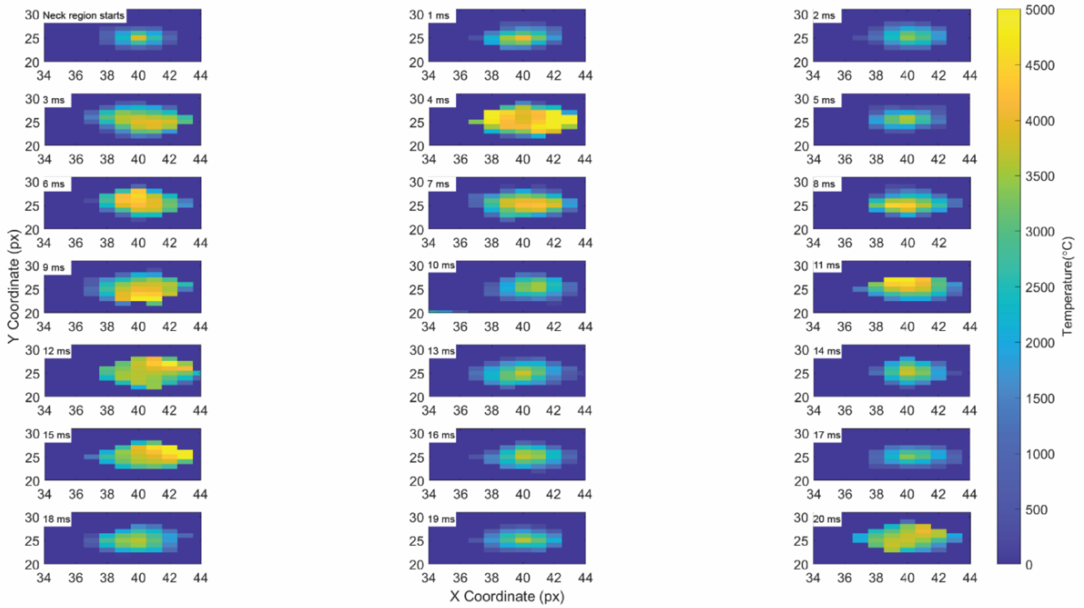


STWIP Application Demo: Result #3: Time-resolved MP Temperature Profiles

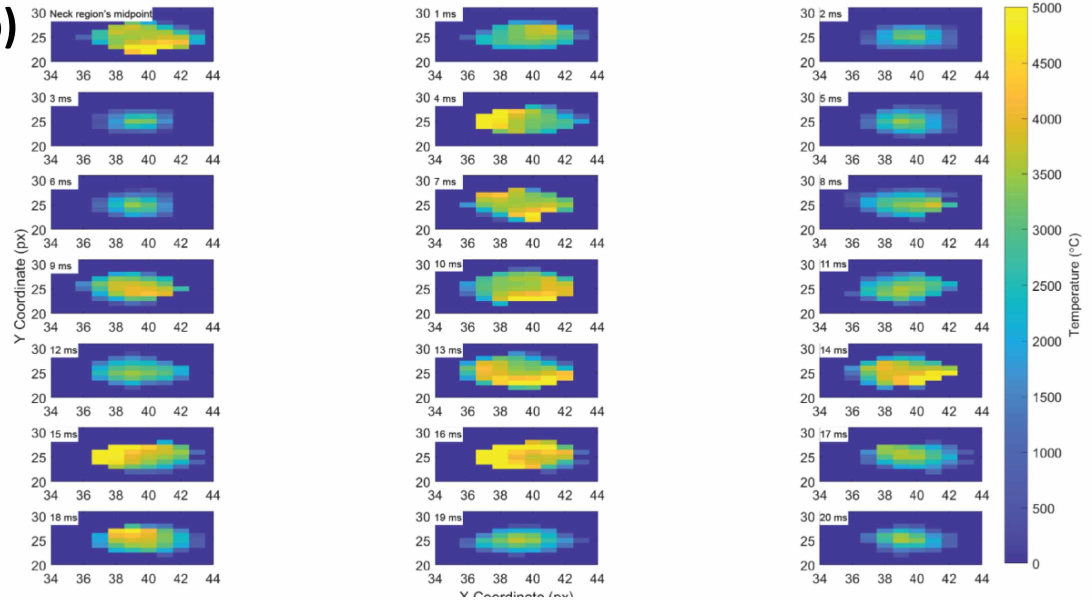
Figure: (a) Schematic showing the MP temperature measurement locations. B indicates Beginning, M indicates Middle portion and E indicates the End portion of the Reduced Section also referred to as Neck region (b) Beginning, (c) Middle and (d) End Neck region's MP temperature profile measured by the developed in-situ system for Layer 14 in a test sample, temporally separated by 1ms.



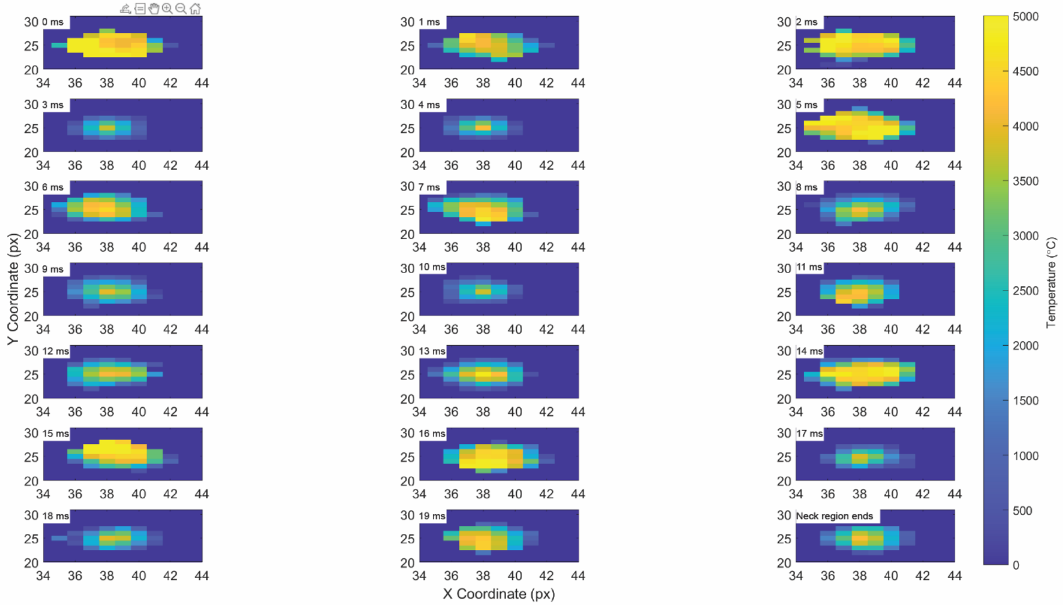
(a)



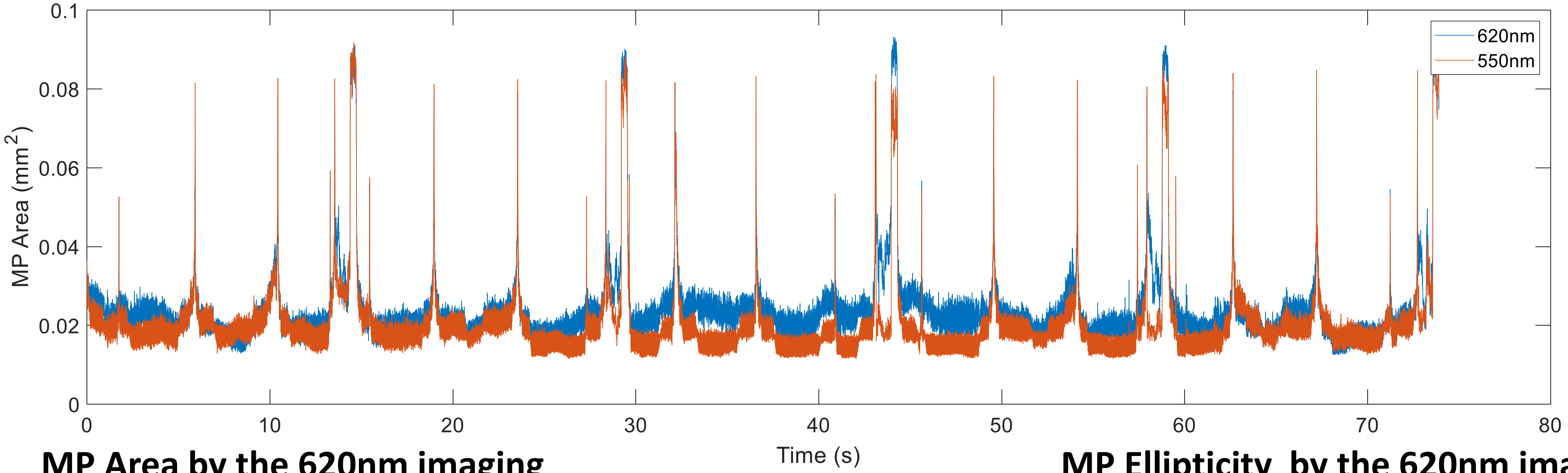
(b)

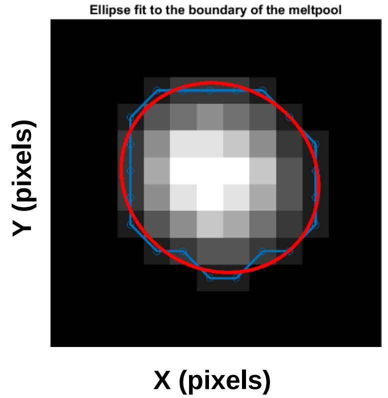


(c)



STWIP Application Demo: Result #4&5: MP Area and Shape (Ellipticity) Profiles

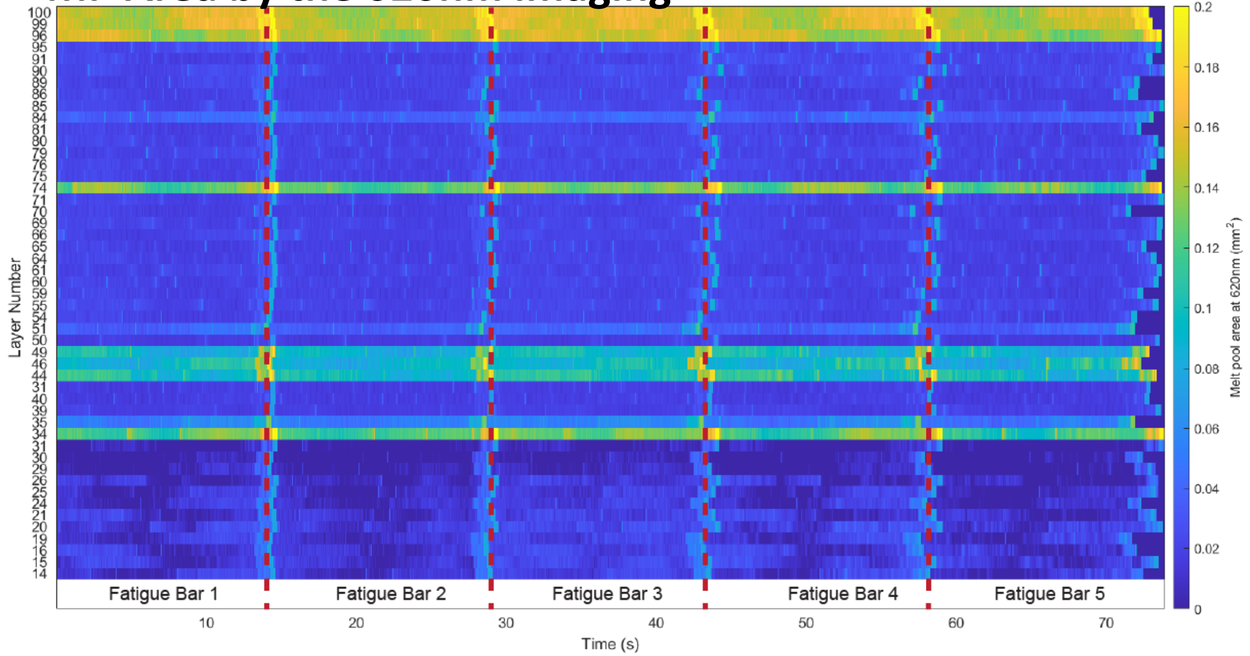




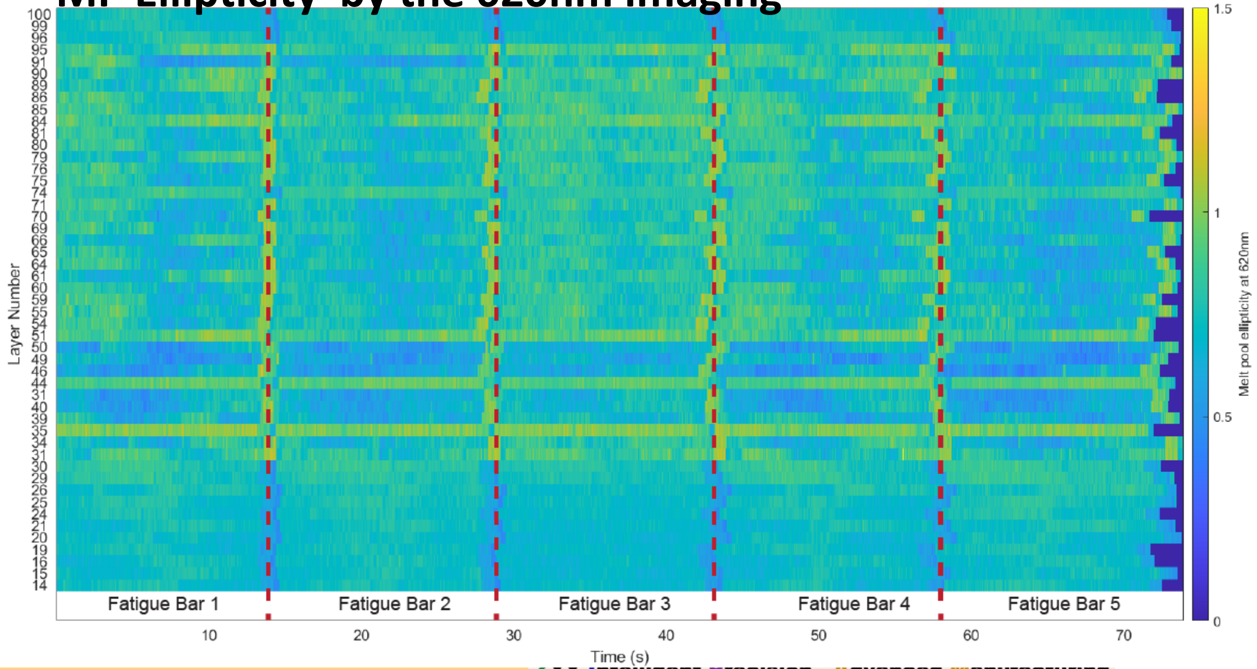
Ellipticity, $e = \sqrt{1-(b^2/a^2)}$

a is the MP length and b is the MP width

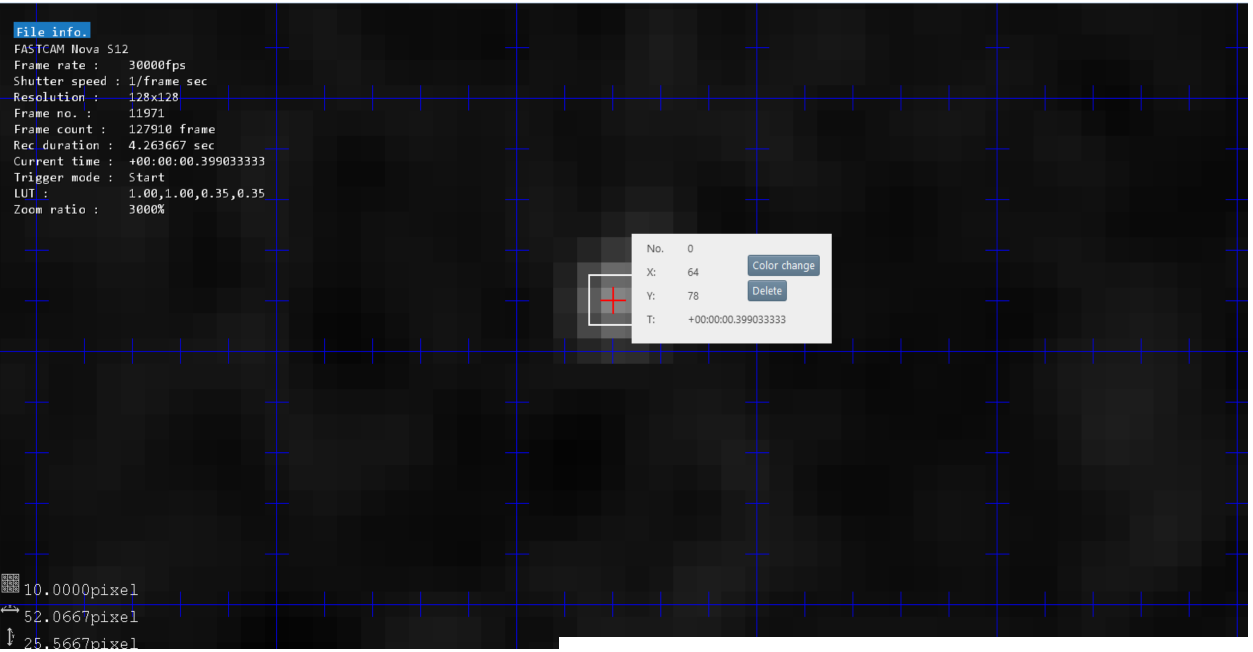
MP Area by the 620nm imaging

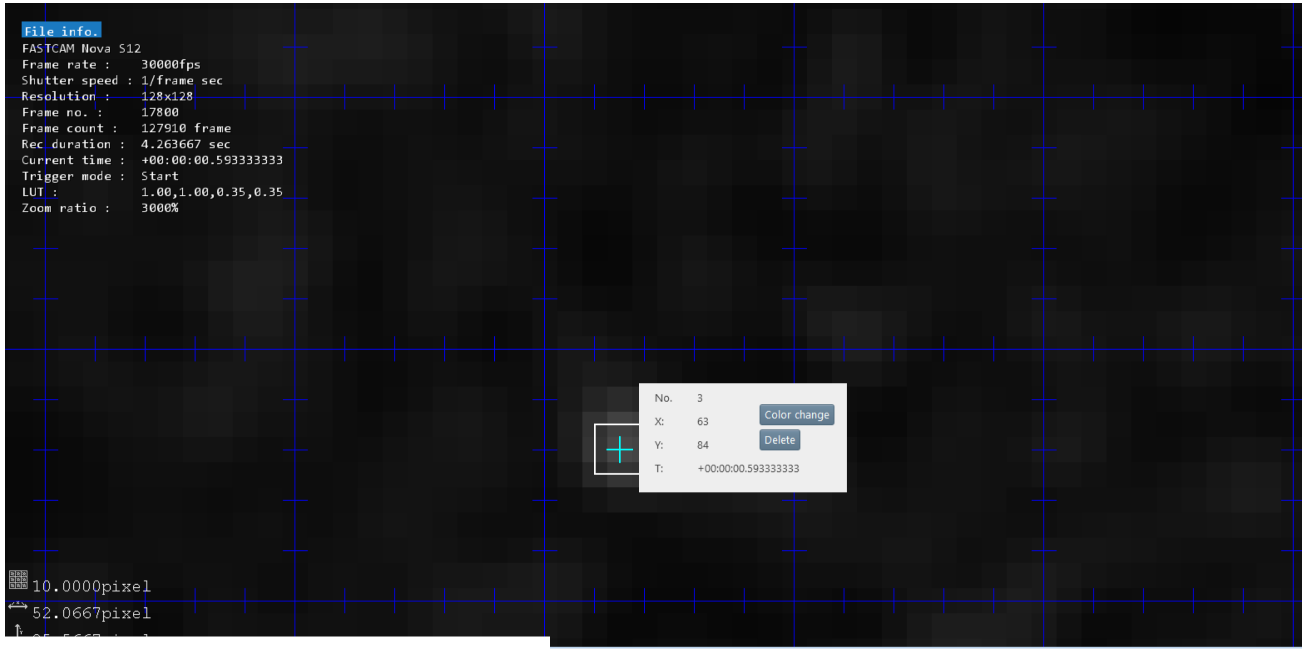


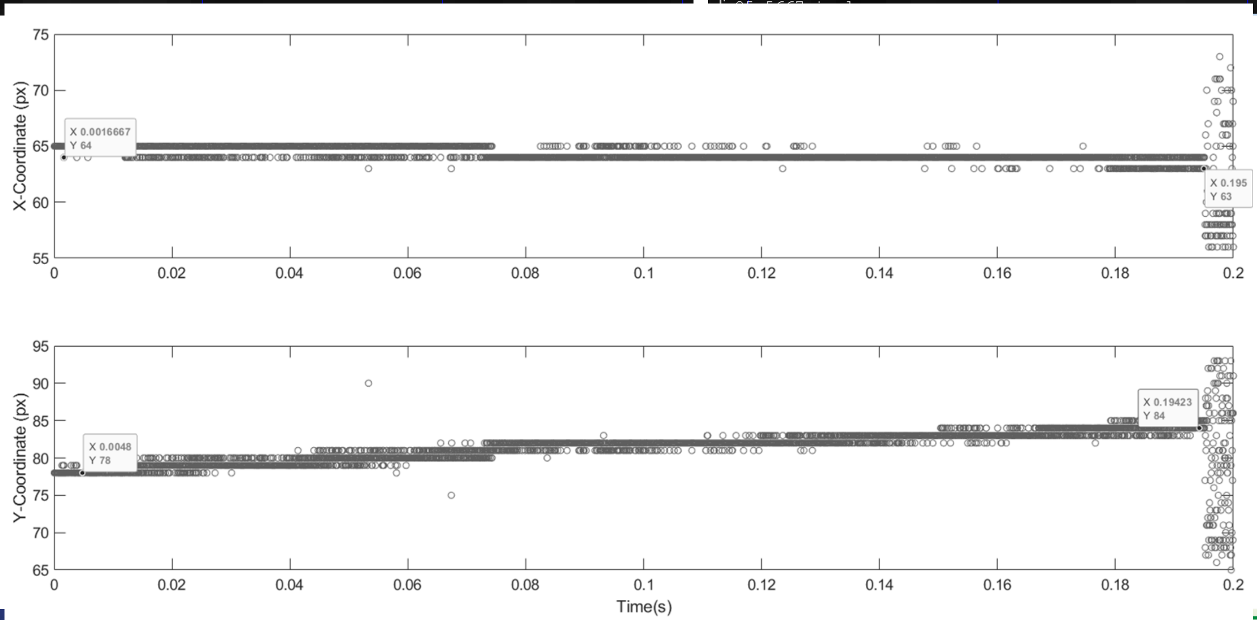
MP Ellipticity by the 620nm imaging



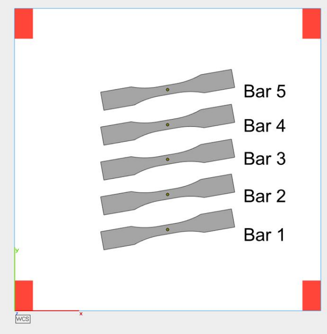
STWIP Application Demo: Result #6: MP Image shifting on the Camera Sensor

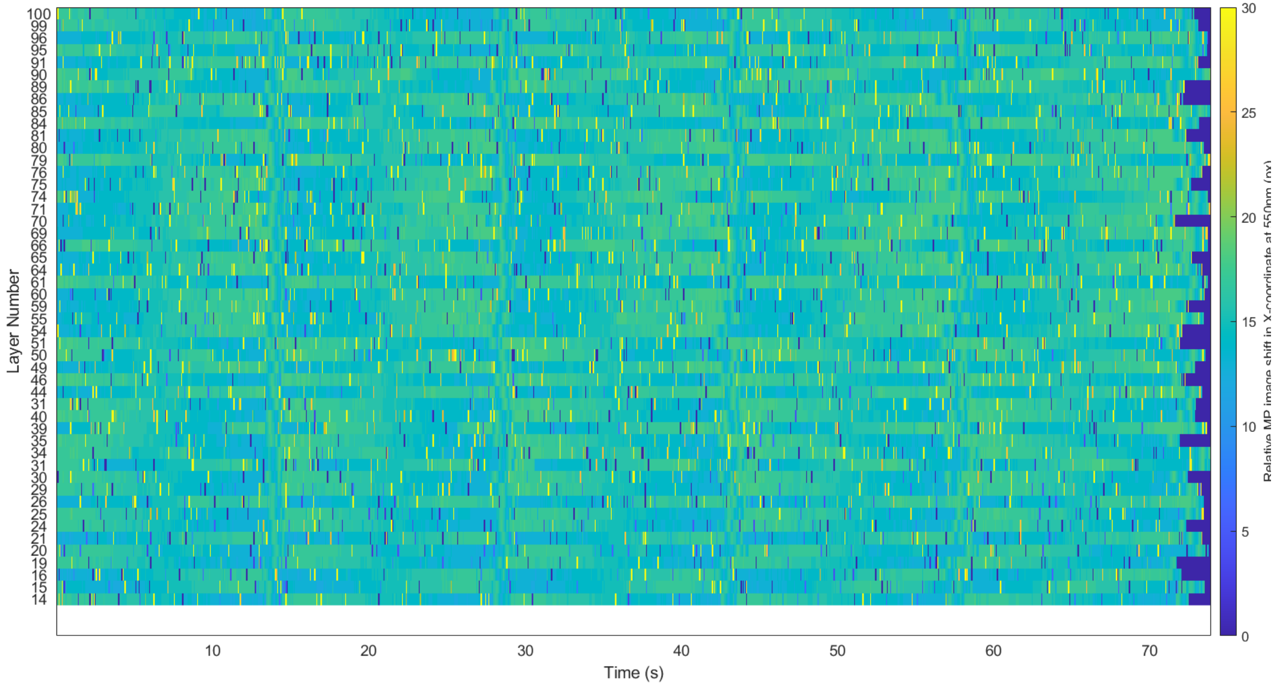


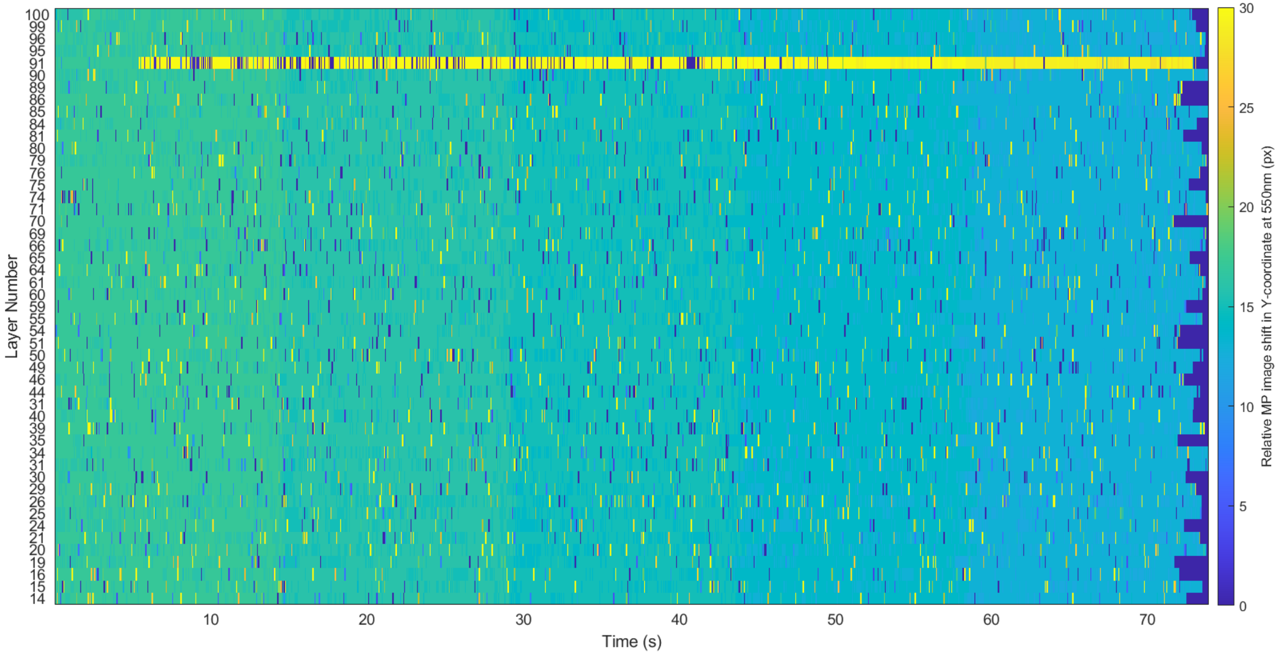




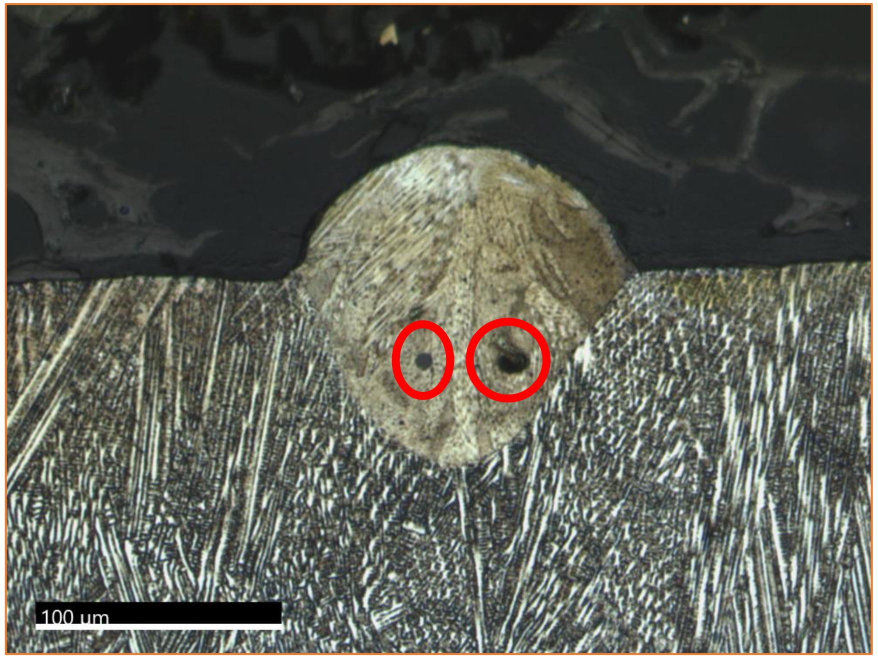
STWIP Application Demo: Result #6: MP Image shifting on the Camera Sensor



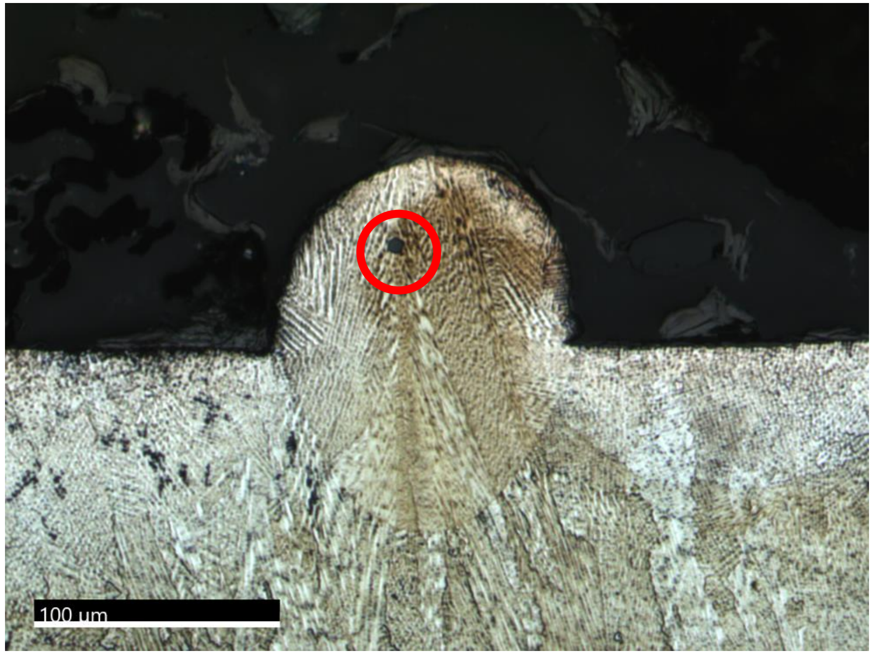




Spattering Porosity

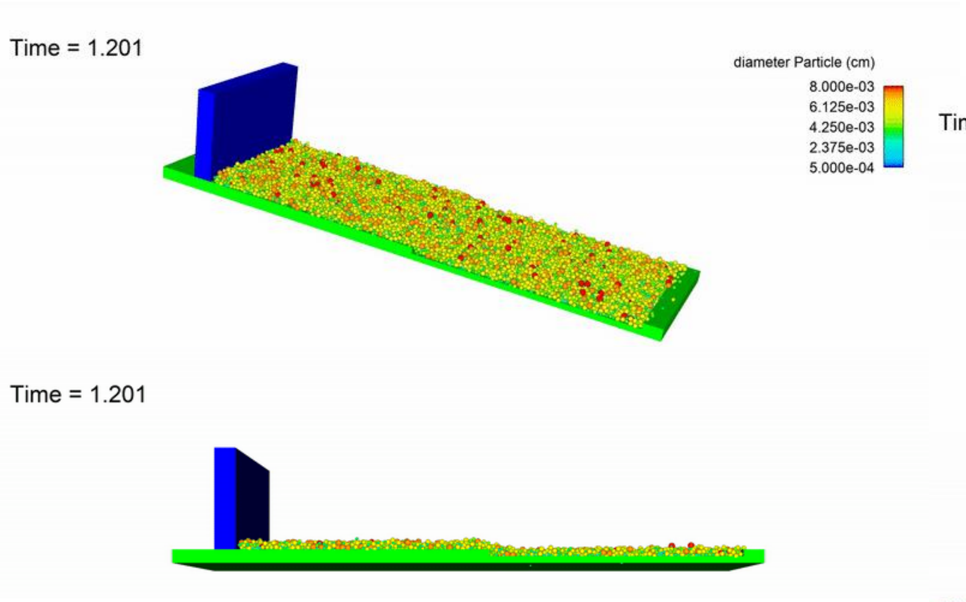


200W_1m/s_1.5 cm high

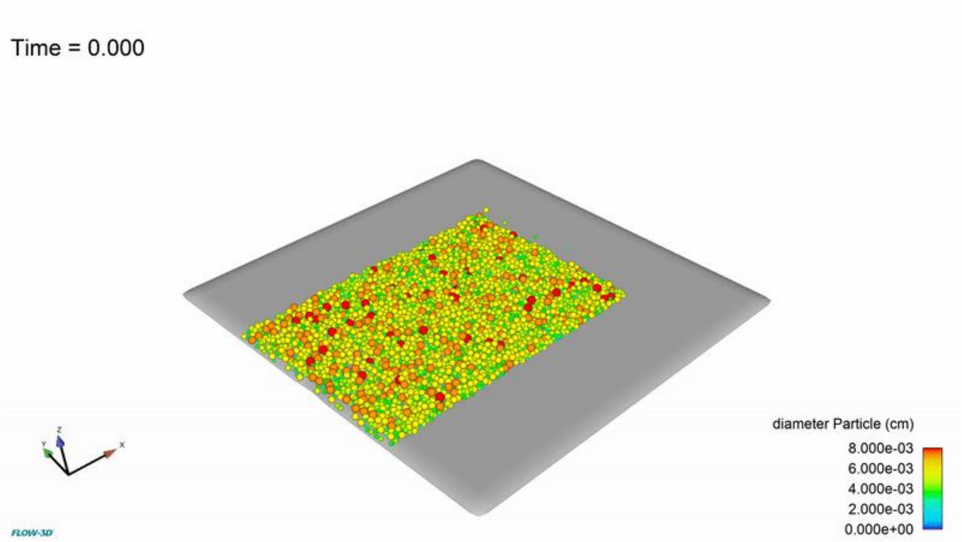


200W_1m/s_5 cm high

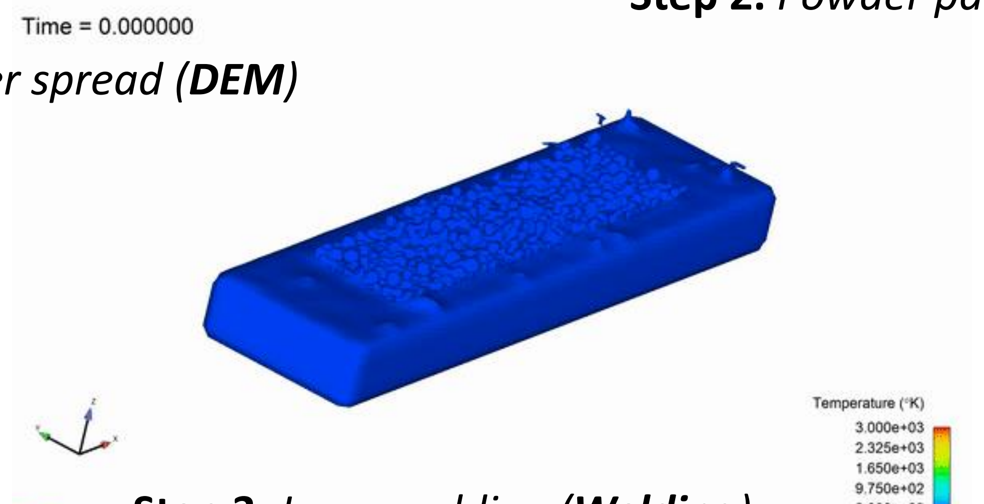
Simulation Flowchart



Step 1. *Powder spread (**DEM**)*

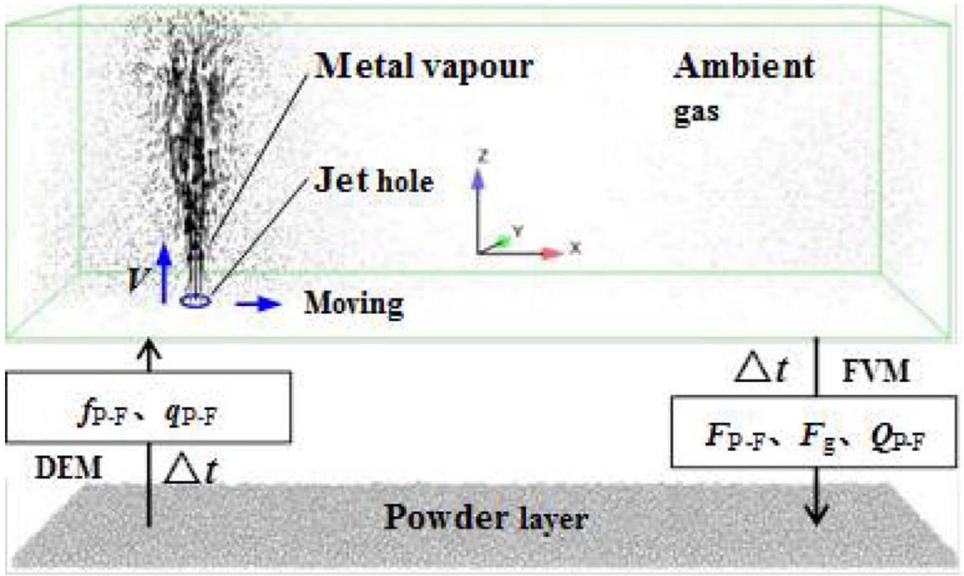


Step 2. *Powder particle spattering (**DEM**)*

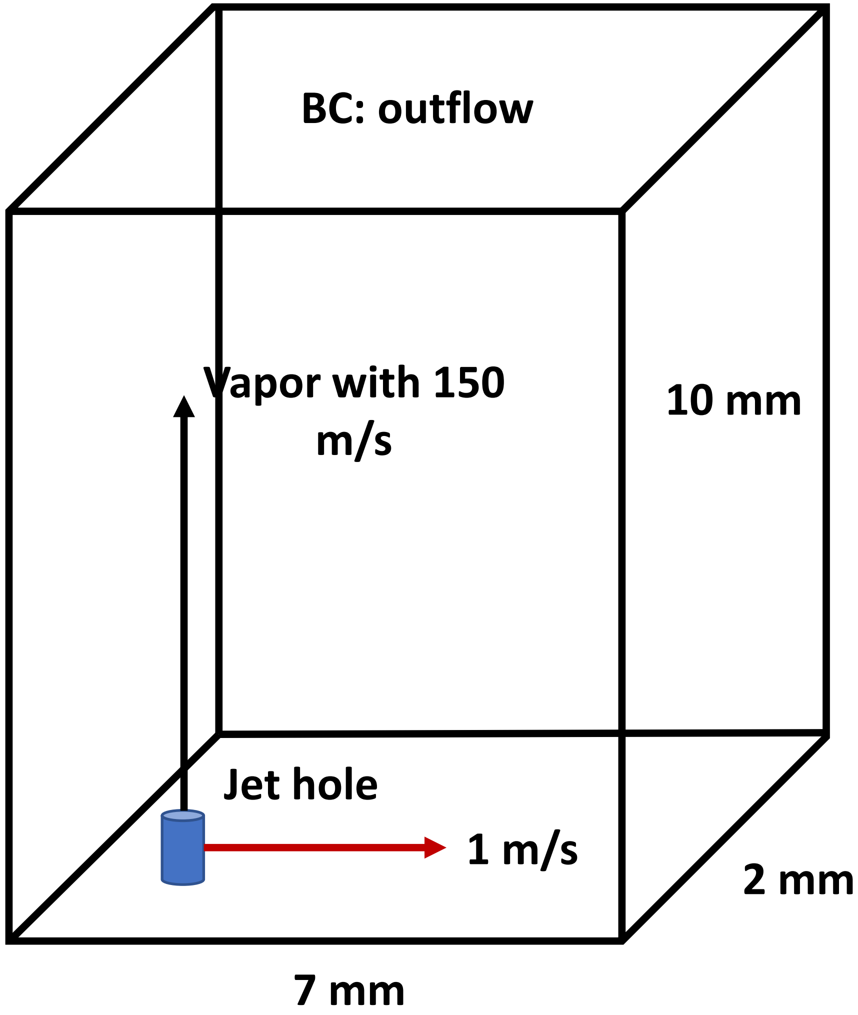


Step 3. *Laser welding (**Welding**)*

Spattering Modeling



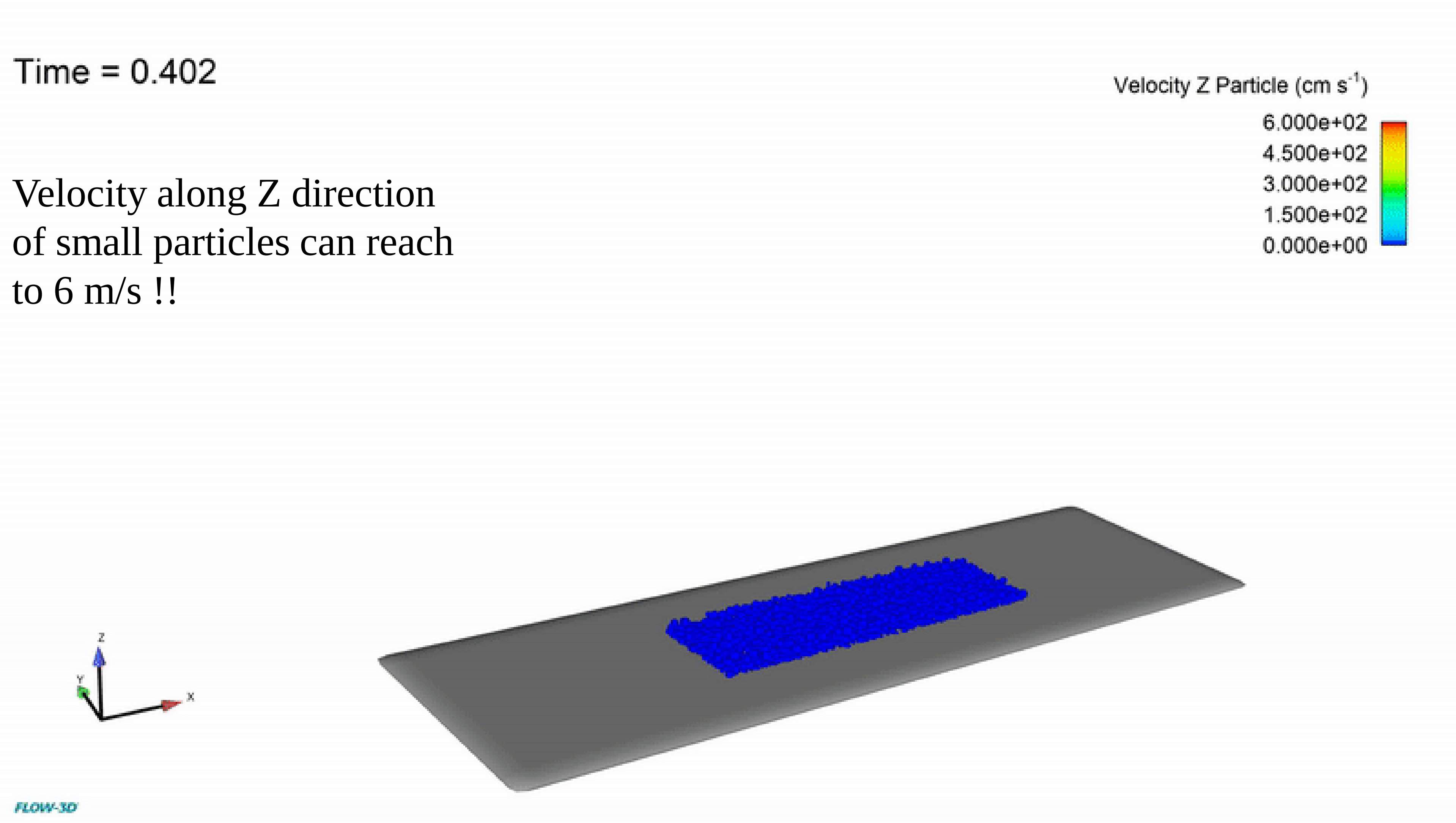
Bi-directional coupling model



Unidirectional coupling model

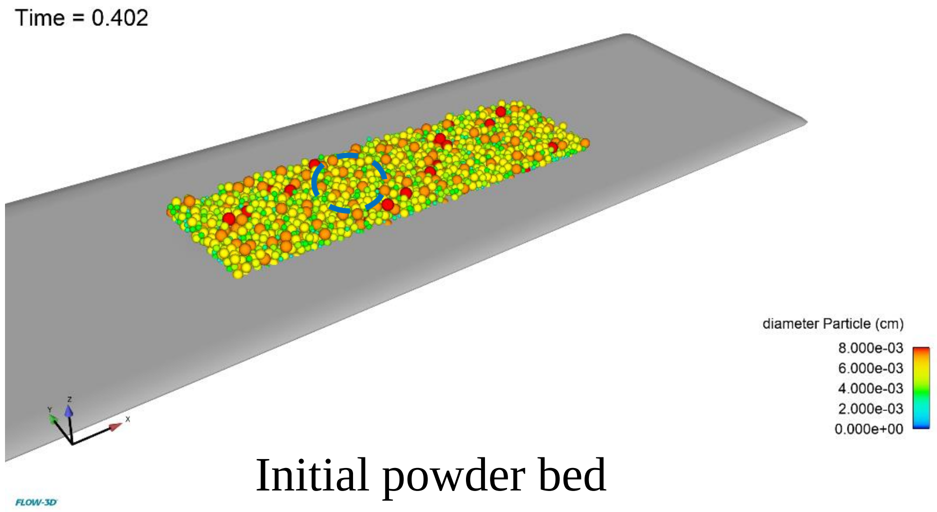
Chen, Hui, et al. Spattering and denudation in laser powder bed fusion process: multiphase flow modelling. Acta Materialia (2020).

Spattering Modeling

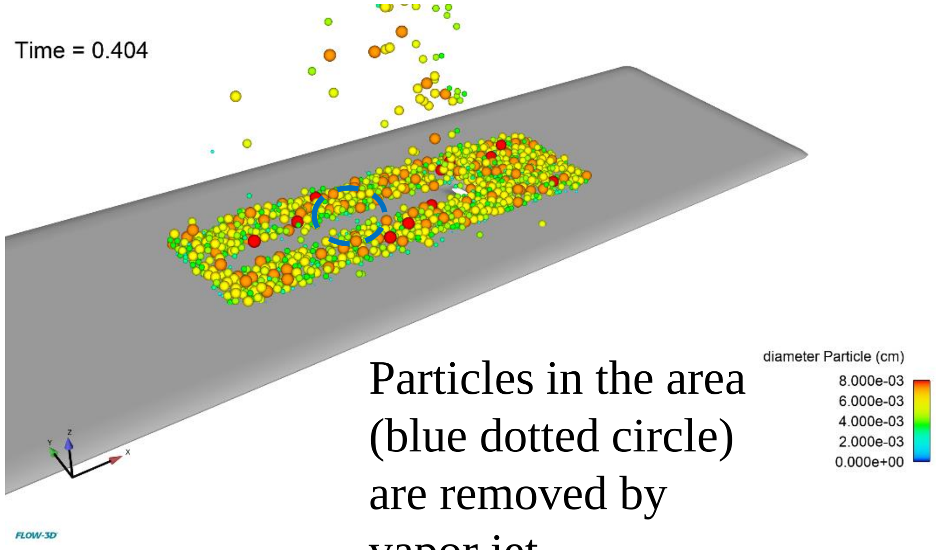


Velocity along Z direction of small particles can reach to 6 m/s !!

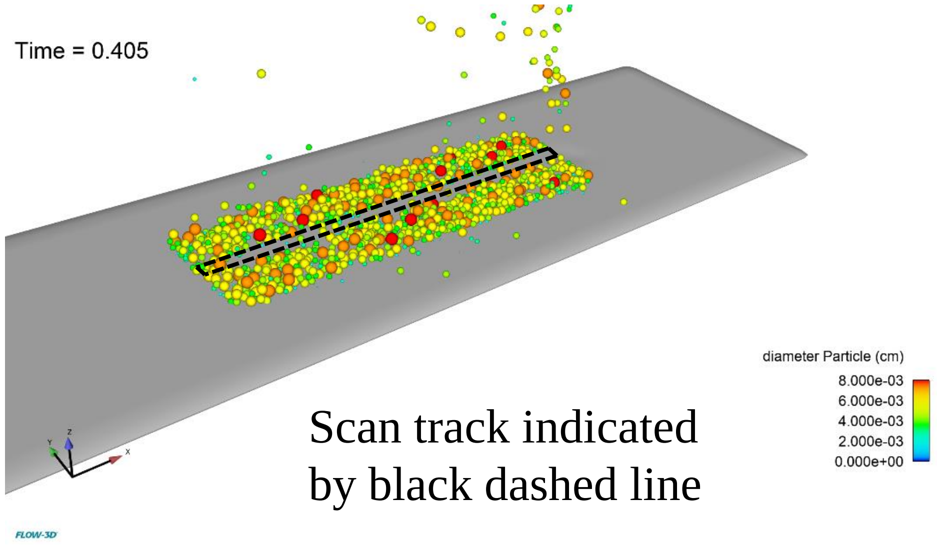
Spattering Modeling



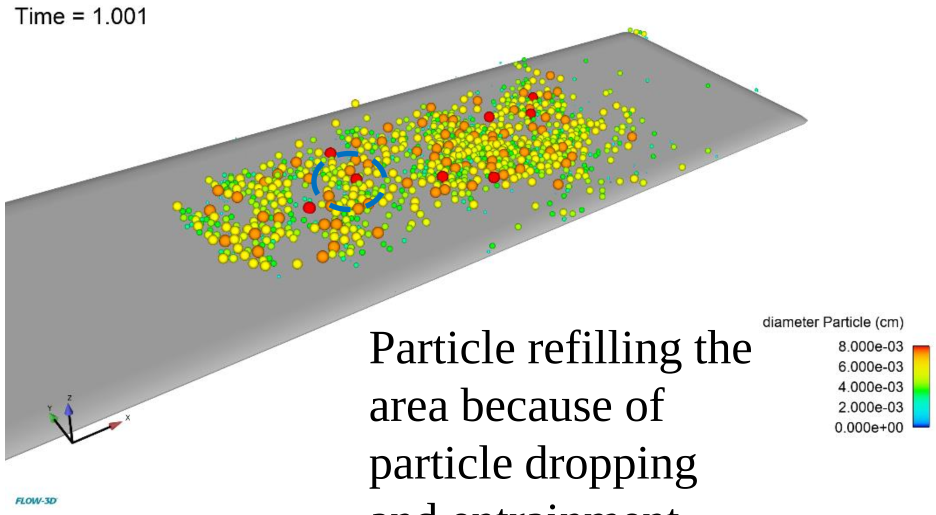
Initial powder bed



Particles in the area (blue dotted circle) are removed by vapor jet

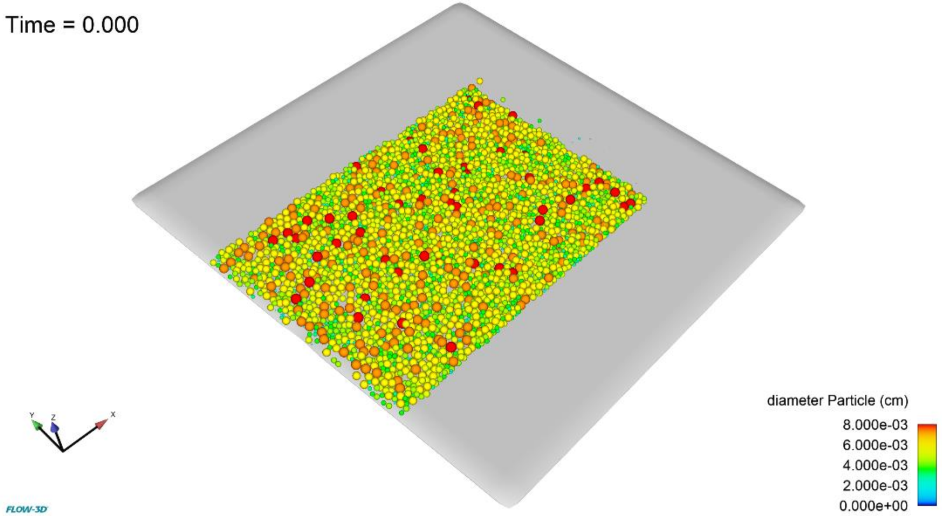


Scan track indicated by black dashed line

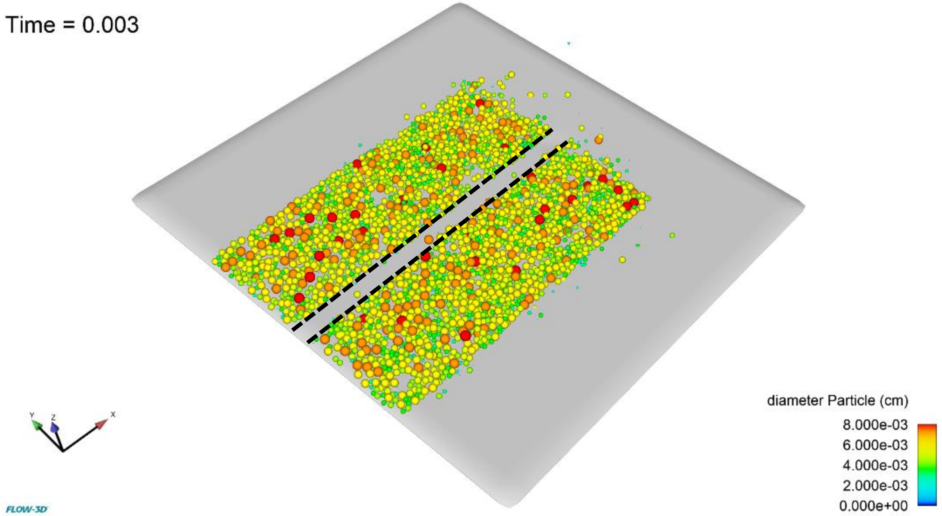


Particle refilling the area because of particle dropping and entrainment

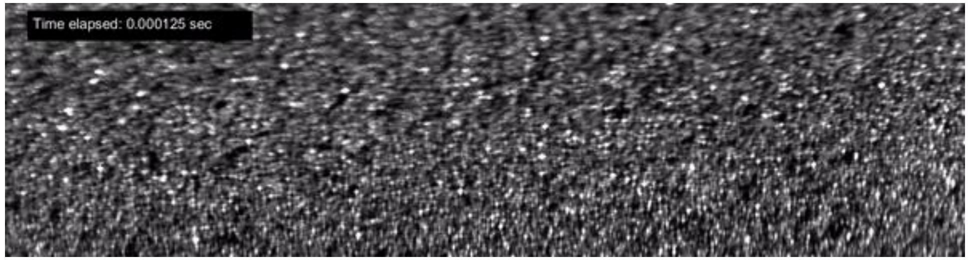
Denudation

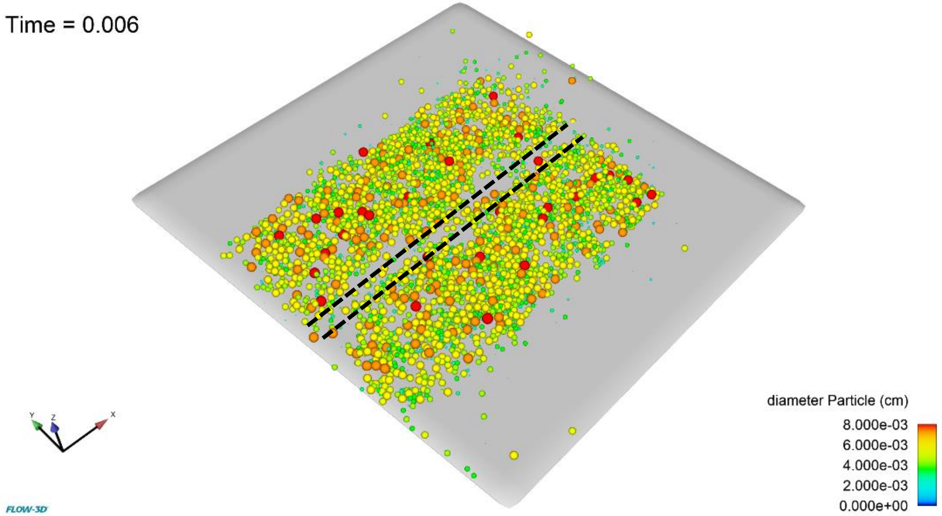


*Original powder bed (**packing density: 53%**)*

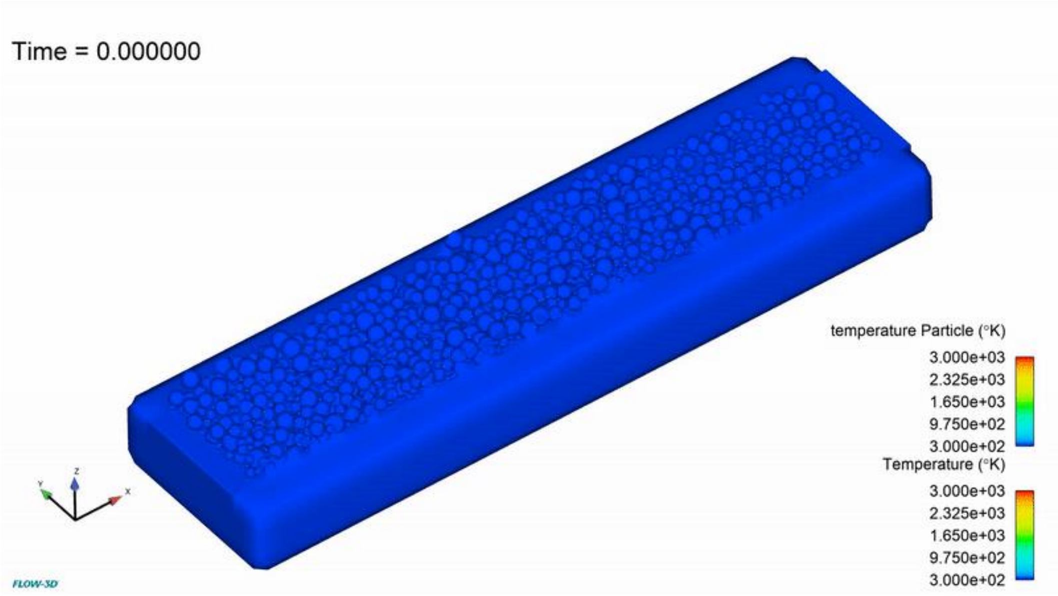


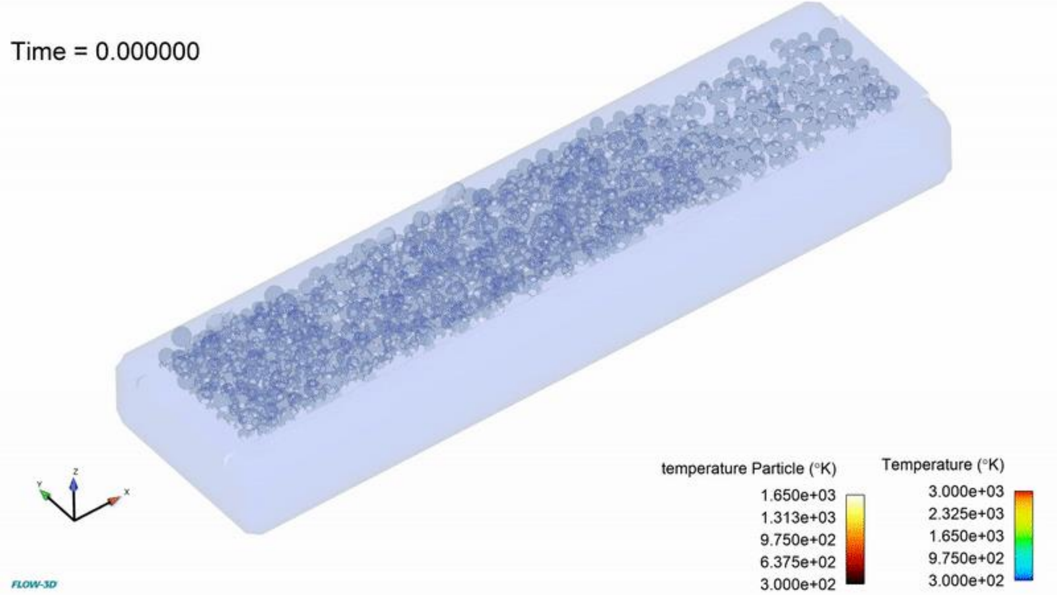
Denudation zone due to vapor jet



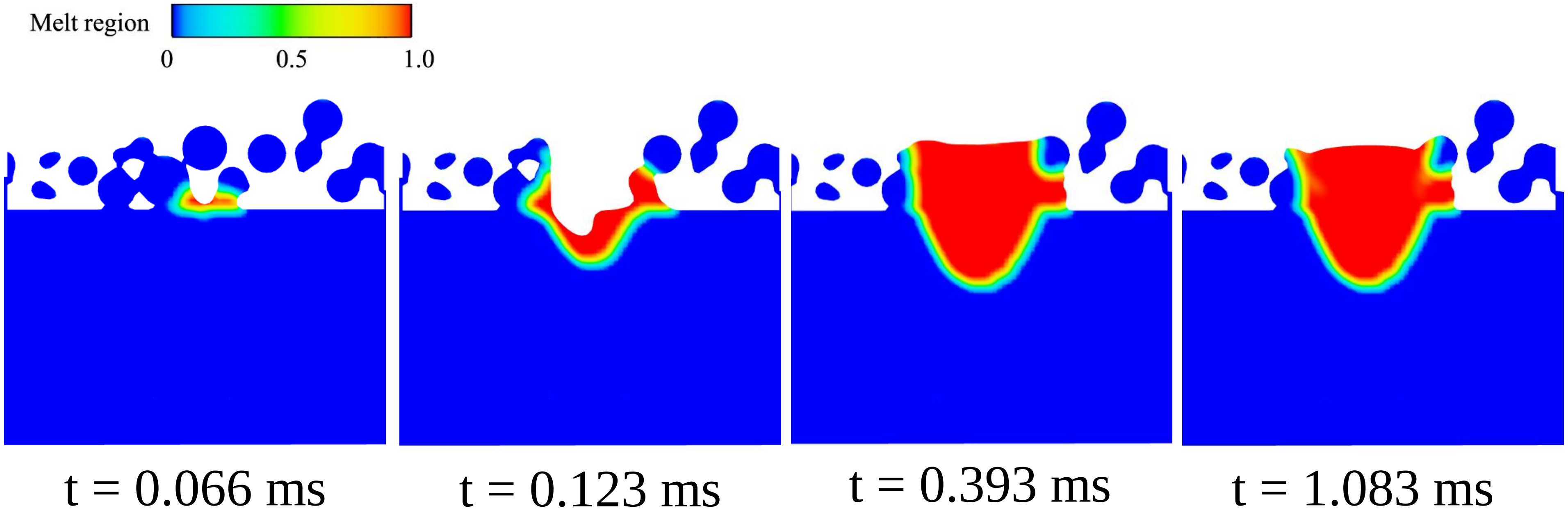


Melt pool simulation with falling spattering particles

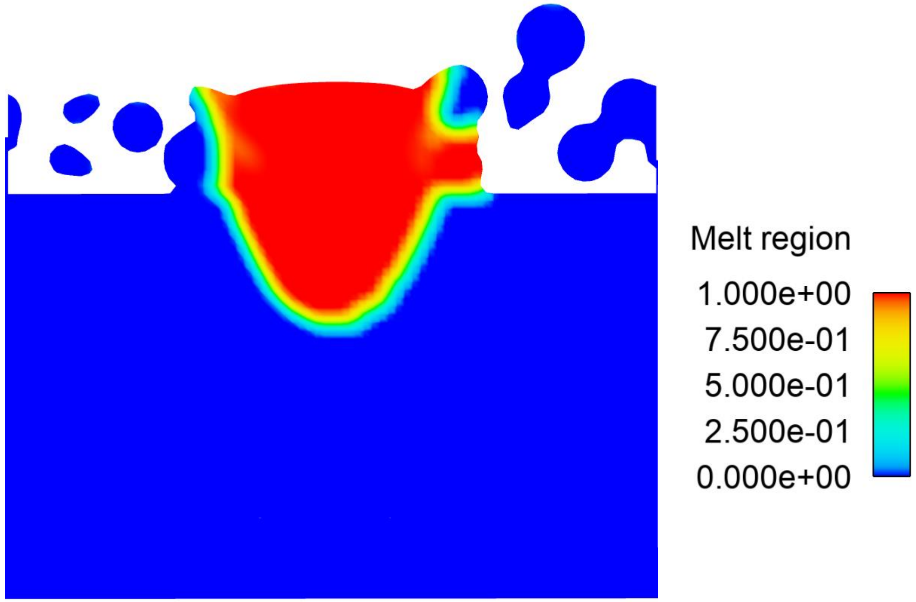


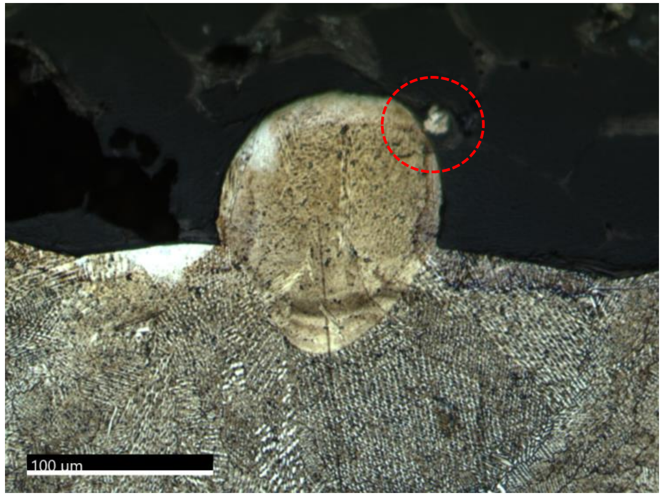


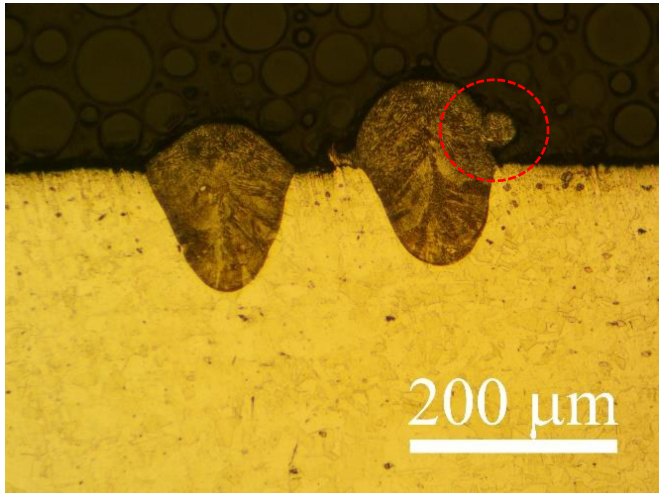
Particle attached to bead



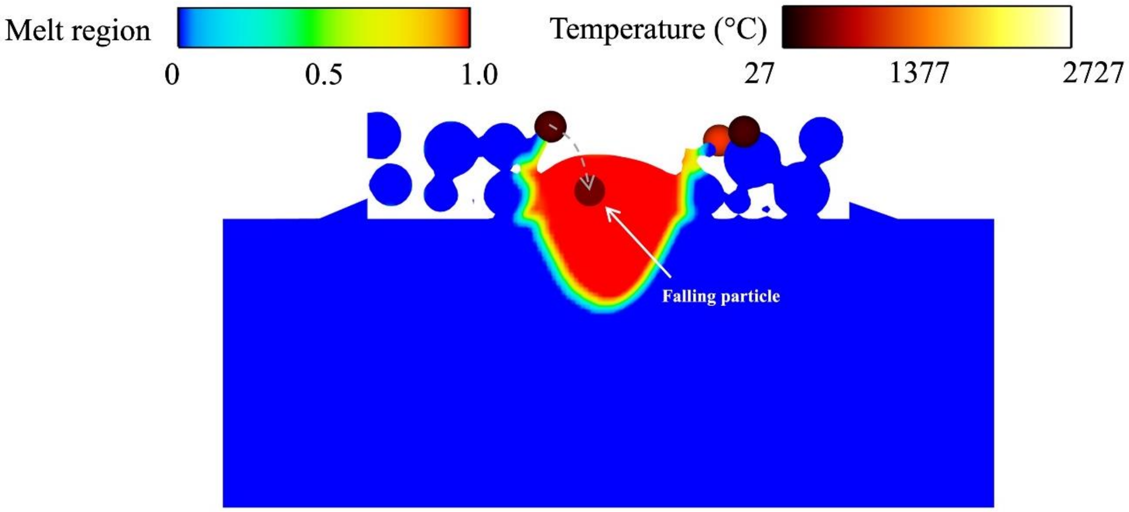
Particle attached to bead

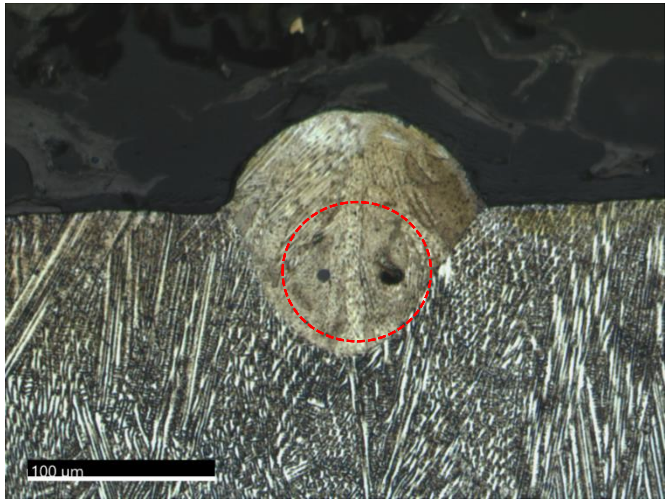


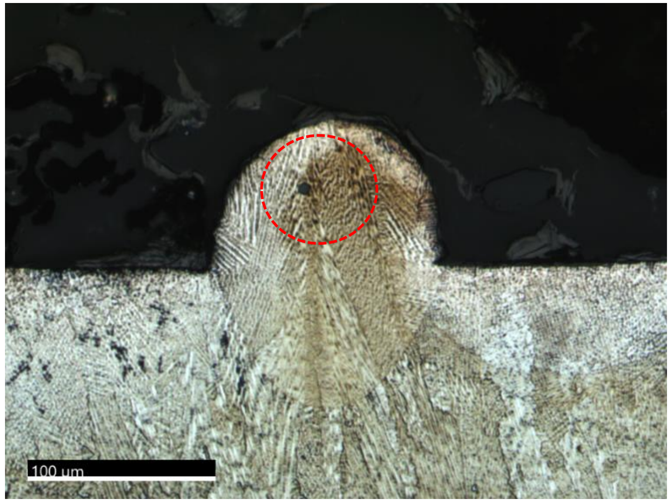




Unmelted particle trapped within bead







Summary

- **Uni-directional coupling simulation is developed by Flow-3D DEM to study the spattering and denudation during laser welding**

- **Coupling simulation is performed to study the interaction between moving laser, powder bed and spattering powder particles**

- **Two pore formation mechanisms are found by simulation and experiments:**
  - **Spattering particle falls into melt pool and remains un-melted**
  - **Spattering particle attached to the melt pool bead**

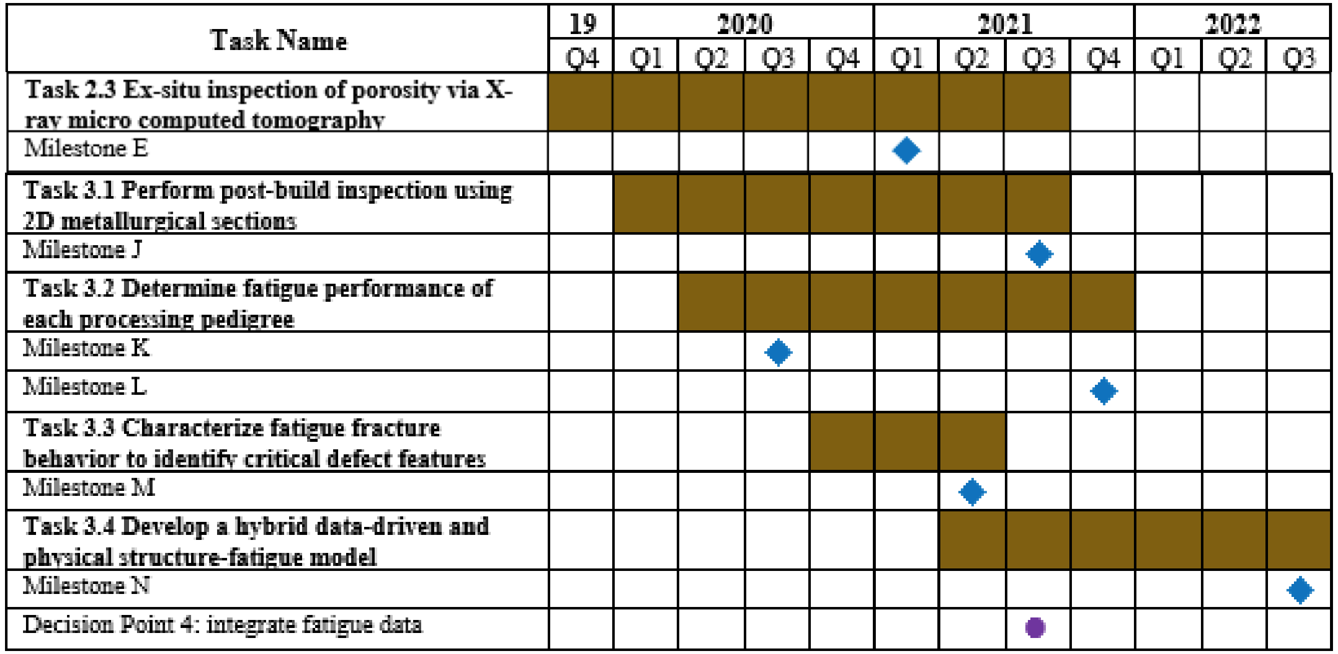
An Effective Quality Assurance Method for Additively Manufactured Gas Turbine Metallic Components via Machine Learning from In-Situ Monitoring, Part-scale Modeling, and Ex-Situ Characterization Data

DOE - University Turbine Systems Research (UTSR)

PI: Xiayun Zhao (University of Pittsburgh)
co-PI: Albert To (University of Pittsburgh)
co-PI: Richard W. Neu (Georgia Tech)

Georgia Tech
CREATING THE NEXT

Project Schedule and Milestones



Task 2.3	**E – Porosity measured in test samples made by different process parameters**	6/30/2021	X-ray micro CT of porosity
Task 3.1	**J - Post-build images acquired**	09/30/2021	Optical micrographs, SEM images in data management system
Task 3.2	**K - Fatigue test protocols established**	09/30/2020	Fatigue testing workflow documented
Task 3.2	**L - Fatigue data acquired**	12/31/2021	Fatigue data in data management system
Task 3.3	**M - Critical defect features identified**	06/30/2021	SEM images with report
Task 3.4	**N - Structure-property model established**	09/30/2022	Optical micrographs, SEM, fatigue tests, report

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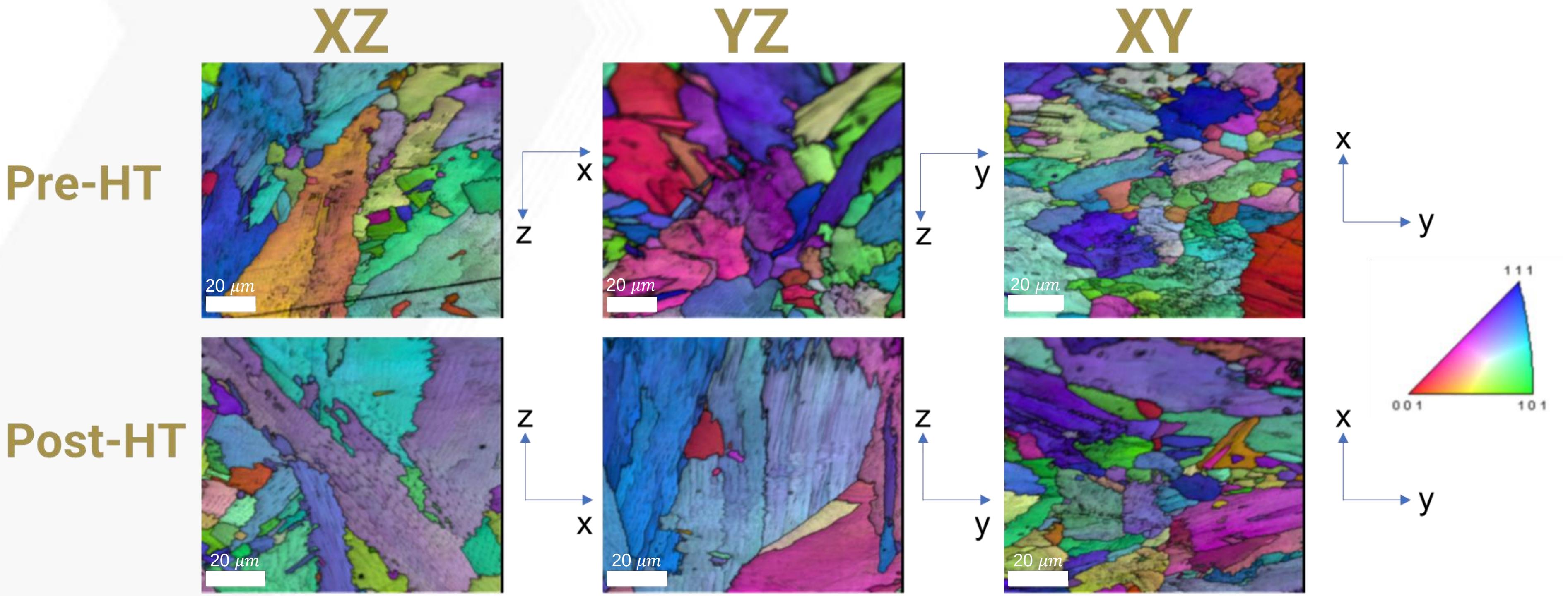
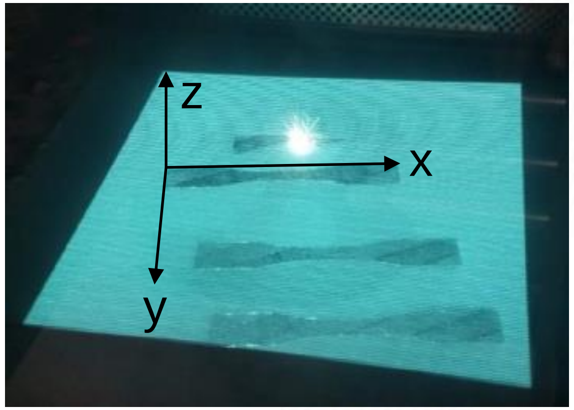
Task 3.1: Perform post-build inspection using 2D metallurgical sections

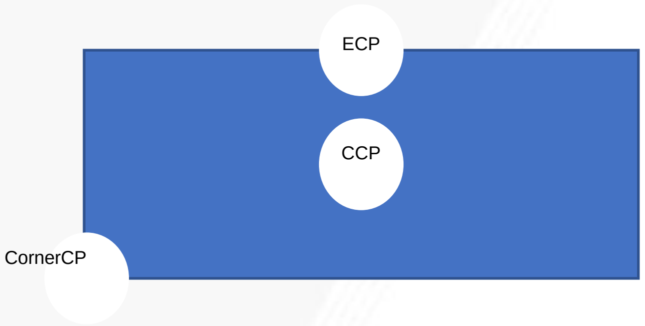
- The heat treatment protocol for all fatigue specimens was established as a direct age procedure involving two steps: (8 h 720℃/FC + 8 h 620℃/AC)
  - This direct age heat treatment was established specifically to nucleate and grow the γ' and γ'' strengthening phases without drastically affecting microstructure on a large scale
- Preliminary EBSD analysis (Build direction = z) showed only minor microstructural change due to heat treatment

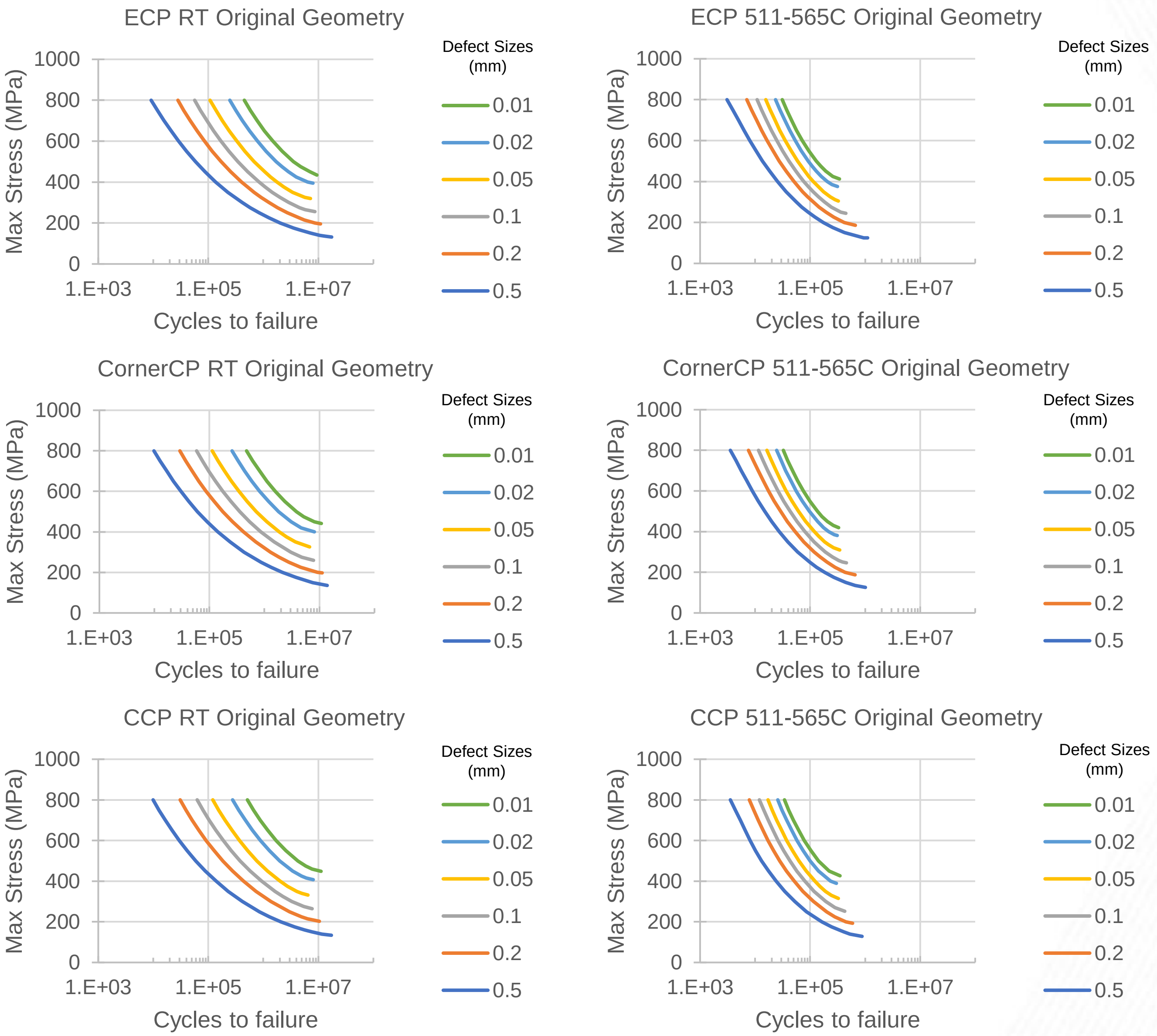




Task 3.2: Determine fatigue performance of each processing pedigree

- Used NASGRO fatigue crack growth prediction software to estimate fatigue life of forged IN718 aged with same heat treatment with varying sizes and types of flaws at RT and at 511-565℃

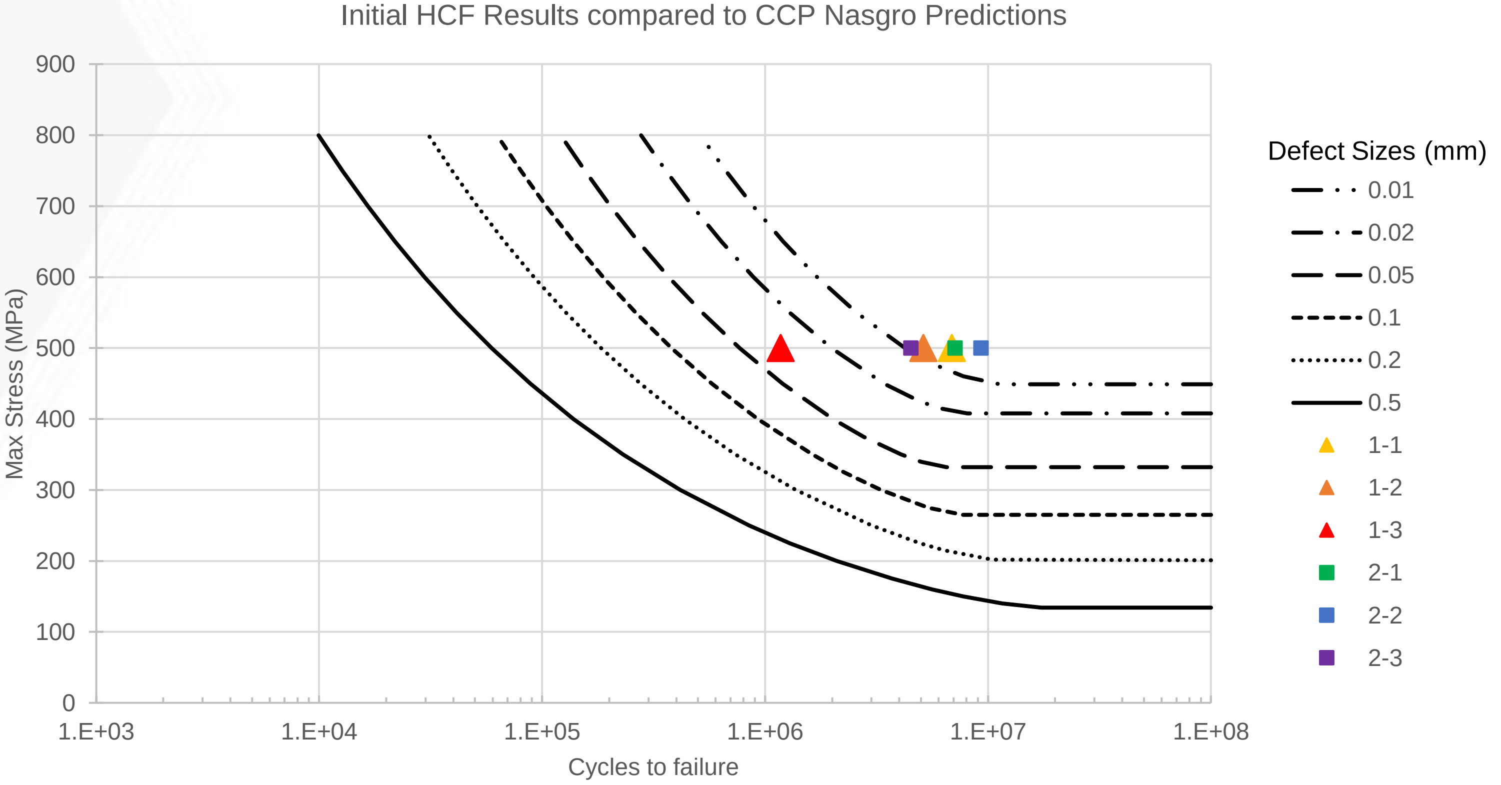




Task 3.2: Determine fatigue performance of each processing pedigree

- HCF testing complete for samples 1-1, 1-2, 1-3, 2-1, 2-2, and 2-3, with a max stress of 500 MPa, R = 0.1 at 20 Hz and RT. Shown below is how the experimental life values compare to the CCP (center crack panel) NASGRO fatigue life predictions
- Results thus far suggest that the flaws that lead to fatigue crack initiation are between 10-50 μm if the fatigue strengths of these additive components can be directly compared to a forged dataset

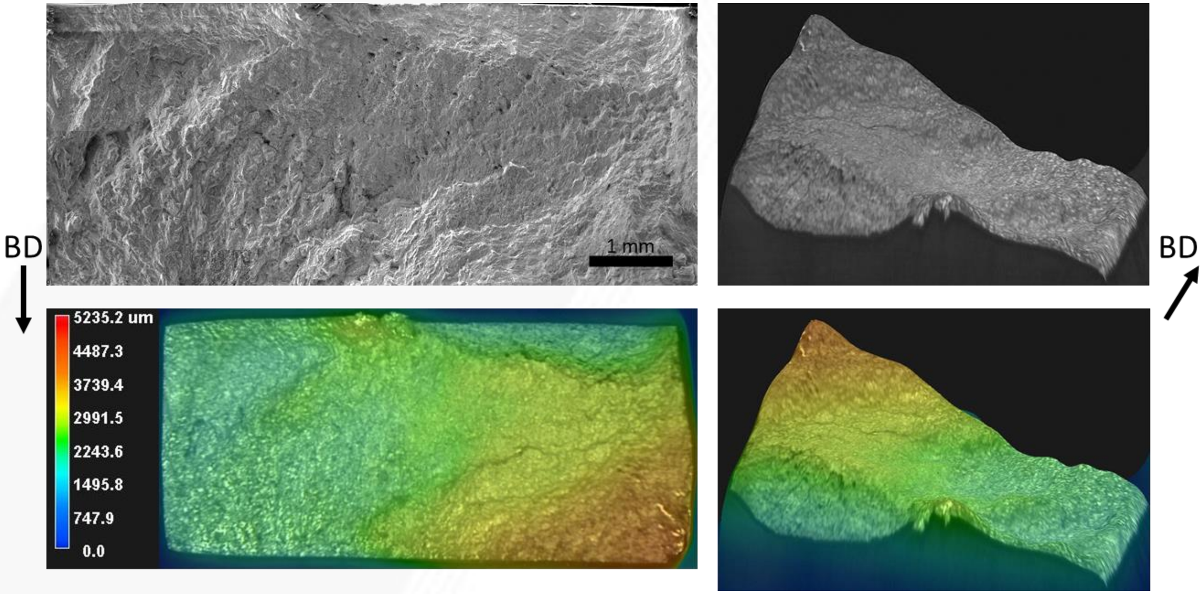
Sample	Fatigue Life
1-1	6895915
1-2	5143257
1-3	1175775
2-1	7121148
2-2	9301502
2-3	4509759



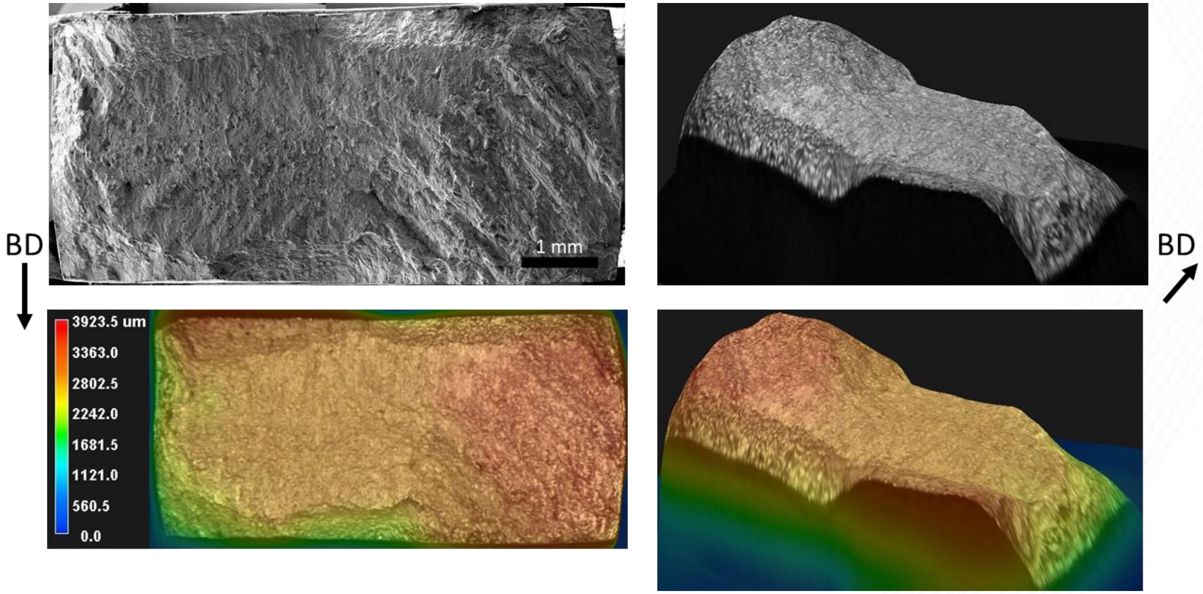
Task 3.3: Characterize fatigue fracture behavior to identify critical defect features.

- Post-mortem fracture surface SEM images and digital microscope scans of sample 1-1 (6.89M cycles) vs. 1-3 (1.17M cycles)

Sample 1-1

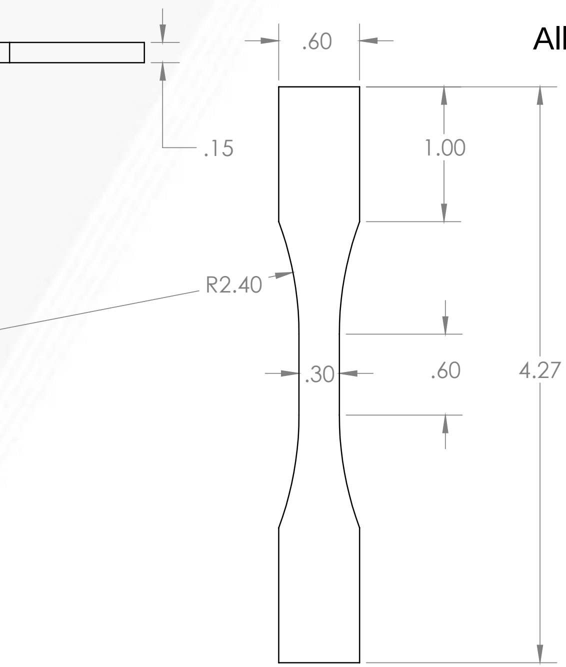


Sample 1-3

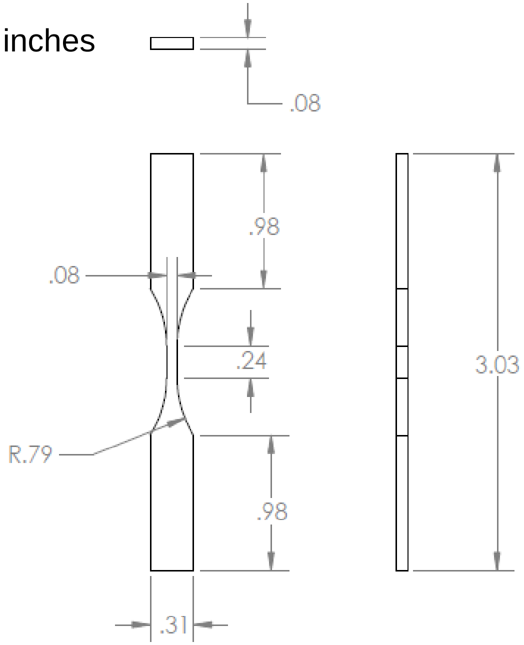


Task 2.3: Ex-situ porosity characterization with micro X-ray CT

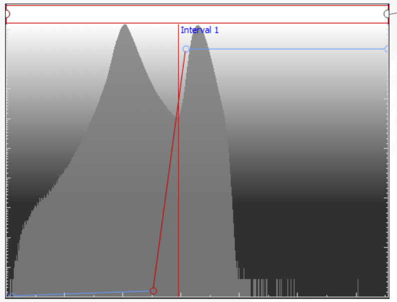
- The original geometry used in builds 1 and 2 was too large to have sufficient xray penetration in the Zeiss Metrotom 800 130 kV
- A reduced gauge section geometry was designed with a thinner cross section in order to allow for better x-ray penetration
- The corresponding pixel intensity histograms next to each geometry show the differentiation between the air (left) and IN718 (right) peaks with the reduced gauge geometry demonstrating better peak separation which corresponds to ability to differentiate a pore from the surrounding material



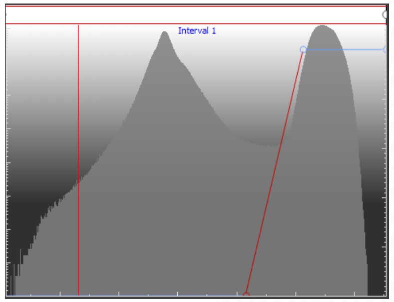
All dimensions in inches



Pixel Intensity Histogram of X-ray Image (poor peak separation)



Pixel Intensity Histogram of X-ray Image (better peak separation)



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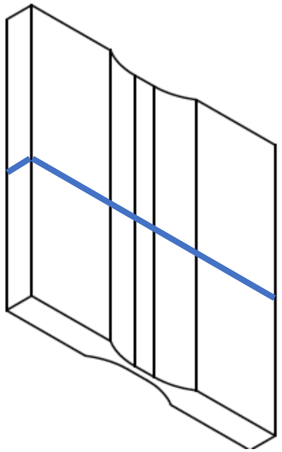
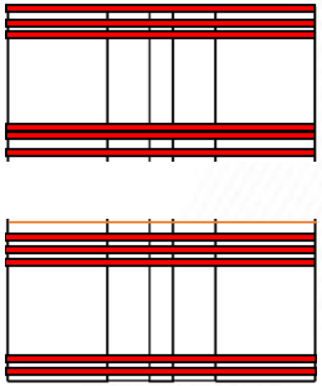
Task 3.2: Determine fatigue performance of each processing pedigree

- Ten sample walls corresponding to the process conditions of sample 6-15 have been heat treated using (8 h 720℃/FC + 8 h 620℃/AC)
- Each wall is being sectioned into various reduced gauge section specimens with heights corresponding to in-situ monitoring data
- Each specimen will undergo XCT to characterize the internal porosity and correlate to anomalies detected in-situ
- Specimens will be tested at 538℃ using similar HCF parameters as previous samples, while others will be tested in creep-fatigue

Sample #	Process Regime	Power (W)	Scan Speed (mm/s)	Hatch spacing (μm)	Volumetric Energy Density (J/mm^3)
6	Transition regime	300	1000	110	68
7	Keyhole regime	350	1000	110	80
8	Keyhole regime	200	500	110	91
9	Keyhole regime	250	500	110	114
10	Keyhole regime	300	500	110	136
11	Conduction regime	200	1000	80	63
12	Conduction regime	200	1000	120	42
13	Keyhole regime	250	500	80	156
14	Keyhole regime	250	500	120	104
15	Conduction regime	200	1500	110	30





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Products (10/2019-Present)

❖ Journal Publications (2)

1. Vallabh, C.K.P. and X. Zhao, *Continuous Comprehensive Monitoring of Melt Pool Morphology Under Realistic Printing Scenarios with Laser Powder Bed Fusion*. ***3D Printing and Additive Manufacturing***, 2021.
2. Qian Chen, Yunhao Zhao, Seth Strayer, Yufan Zhao, Kenta Aoyagi, Yuichiro Koizumi, Akihiko Chiba, Wei Xiong, Albert To. *Elucidating the effect of preheating temperature on melt pool morphology variation in Inconel 718 laser powder bed fusion via simulation and experiment*. ***Additive Manufacturing.*** 2020.

❖ Conference Papers/Presentations (3)

1. **[invited talk]** X. Zhao, "***Combined in-situ monitoring of meltpool, powder layer, and part topography for laser powder bed fusion (LPBF) based metal additive manufacturing***", Materials Science & Technology 2021, Columbus, Ohio, October 19, 2021.
2. Q. Chen, S. Strayer, A. C. To, "***Pore formation in laser powder bed fusion Inconel 718 through multiphysics modeling***", Materials Science & Technology 2020, Virtual, November 2-6, 2020
3. Vallabh, C.K.P., Y. Xiong, and X. Zhao. ***In-situ Monitoring of Laser Powder Bed Fusion Process Anomalies via a Comprehensive analysis of off-axis Camera Data***. in *Proceedings of ASME 2020 International Manufacturing Science and Engineering Conference*. 2020. Cincinnati, Ohio, USA.

❖ Inventions (1 Patent Application)

- Zhao, X., and Vallabh, C.K.P. (USPTO 17/015,062, filed on September 8, 2020) ***Systems and Methods of Adaptive Two-wavelength Single-camera Imaging Thermography (ATSIT) for Accurate and Smart in-situ Process Temperature Measurement during Metal Additive Manufacturing*** (University of Pittsburgh).

Dissemination to Communities of Interest

Time	Event & Venue	Primary Audience	Activity and Impact
11/2019	SciTech Exhibition at Carnegie Science Museum	K-12 Children	PI Zhao's group demonstrated metal 3D Printing and Computer Vision based monitoring technologies
03/2020	Women in 3D Printing – Pittsburgh Chapter Workshop at Pitt	Industry partners, University students	PI Zhao gave a presentation on "Additive Manufacturing Qualification" introducing part of this project research and results.
07/2020	ASPE (American Society of Precision Engineering) Summer Topical Workshop on Additive Manufacturing	ASPE members, including University and National Lab Researchers and industry attendees across the world	PI Zhao introduced and acknowledged this DOE NETL sponsored research project on in-situ monitoring and qualification of metal AM
05-06/2021	Pittsburgh Science and Technology Academy	Grades 6-12	PI Zhao presented two webinars on "Additive Manufacturing and Metrology" to junior-high school students for increasing their knowledge and interest in STEM.

Acknowledgement

- DOE NETL UTSR Program (Grant Number: DE-FE0031774)
- Project Manager: Mark C. Freeman
- University of Pittsburgh Swanson School of Engineering
- Co-PIs: Prof. Albert To (Pitt), Prof. Richard Neu (GaTech)
- Industry Partners: Turbine Manufacturer, ANSYS