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In-Process Sensing of Laser Powder Bed Fusion Additive Manufacturing

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Presenter: ***Yu-Ping Yang***

A Workshop on Predictive Theoretical and Computational Approaches for Additive Manufacturing
Keck Center, Room K-100
500 Fifth St. NW Washington, DC

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Acknowledgement: In Process Monitoring Team

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Outline

- Why in-process sensing of Laser Powder Bed Fusion (L-PBF) additive manufacturing is important
- How to develop in-process sensing technology
- Application of in-process sensing to monitor L-PBF
- How in-process sensing improves numerical model prediction
- Sensing development status

Conventional Manufacturing Techniques

melt

form

finish

- **Conventional material production steps are tightly monitored and controlled to ensure quality.**
- **AM is Materials Creation…directly into a functional part.**

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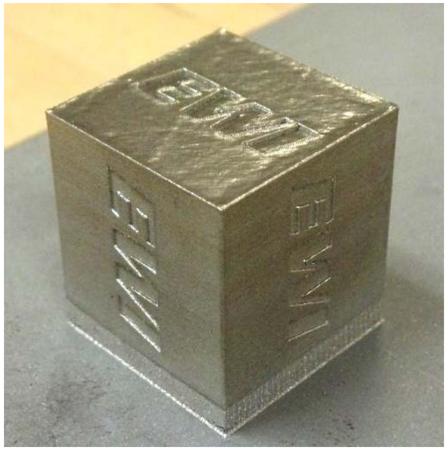
Why is In-Process Monitoring Needed?

1-inch L-PBF Cube



5 miles of weld

- **Each weld is an opportunity for a defect**
- **Hours/days/weeks of build time**
- **Post process inspection can be difficult and costly**
- **In Process Sensing is necessary to move 3DP to AM**

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Approach to Process Sensing

- **Without sensing:**
  - Rely on process development.
  - Rely on Post-Process Inspection
- **Incremental approach to material creation allows:**
  - Sensing of defects when they are created
  - Access to difficult to inspect areas.
  - Opportunities to cancel long builds.
- **Sense first, control second.**
- **Monitor:**
  - KPP’s (Before, During, and After)
  - Local Material/Process Interactions
  - Global Material/Process Interactions

Problem Statement and Objective

- **Problem Statement:** Laser Powder Bed Fusion (L-PBF) systems do not possess the same level of quality monitoring that conventional manufacturing systems employ
- **Objectives:** Evaluate and mature in process sensing techniques on a L-PBF Sensor Test Bed to:
  - Enable quality monitoring
    - Process deviations
    - Geometry, distortion, and bed flatness
    - Metallurgical
    - Pores/Lack of fusion/Cracking
  - Create experimental measurements for validating numerical models of L-PBF

Technical Approach

- **Develop a L-PBF test bed**
  - It is difficult to install senses in commercial L-PBF machine
  - Therefore, a L-PBF test bed was developed to allow for sensor evaluation without physical or software constraints
- **Install local sensors**
  - Monitor the area near the point of material fusion
- **Install global sensor**
  - Defect occurrence over entire bed
- **Test sensors**
  - Produce thermal images
  - Produce optical images

A Commercial L-PBF machine:

- EOS M280 with 400W laser for L-PBF at EWI

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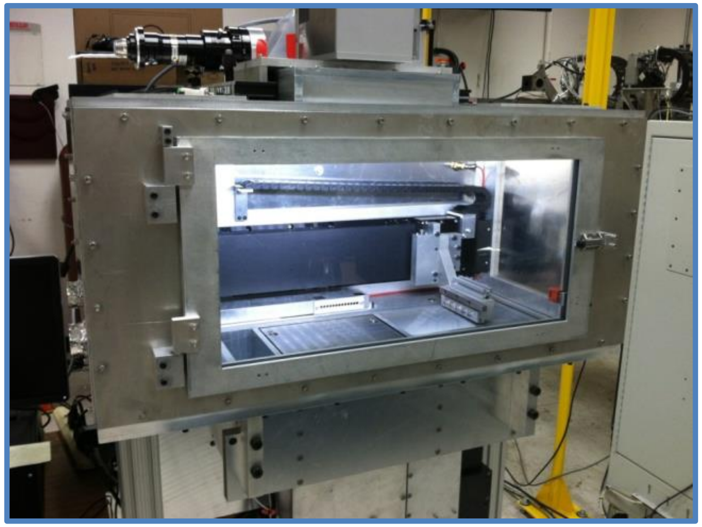
Develop a L-PBF Test Bed

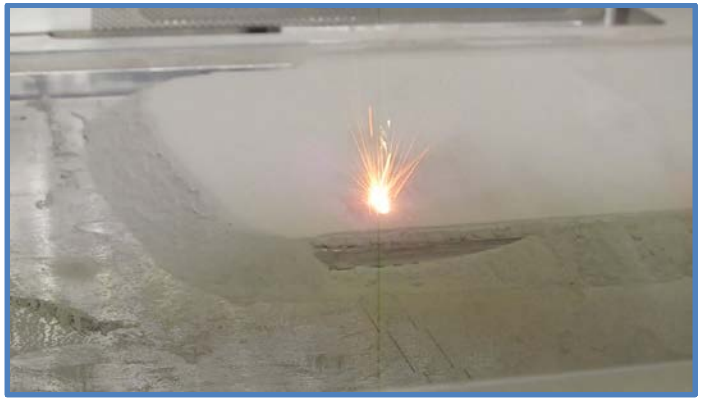
1. **Design and fabricate test bed**
2. **Evaluate the test bed**

Design and Fabricate Test Bed

Design → Fabricate → Evaluate

- **HARDWARE**
  - Checked positional axes to be within 10um resolution
  - Determined laser focus position, power calibration
  - Completed build platform leveling
- **CONTROLS**
  - All motor drives, solenoids, PCs, sensor COM, power, etc., integrated into control cabinet
  - 1 PC for sensor test control
  - 1 PC for sensor data acquisition and display





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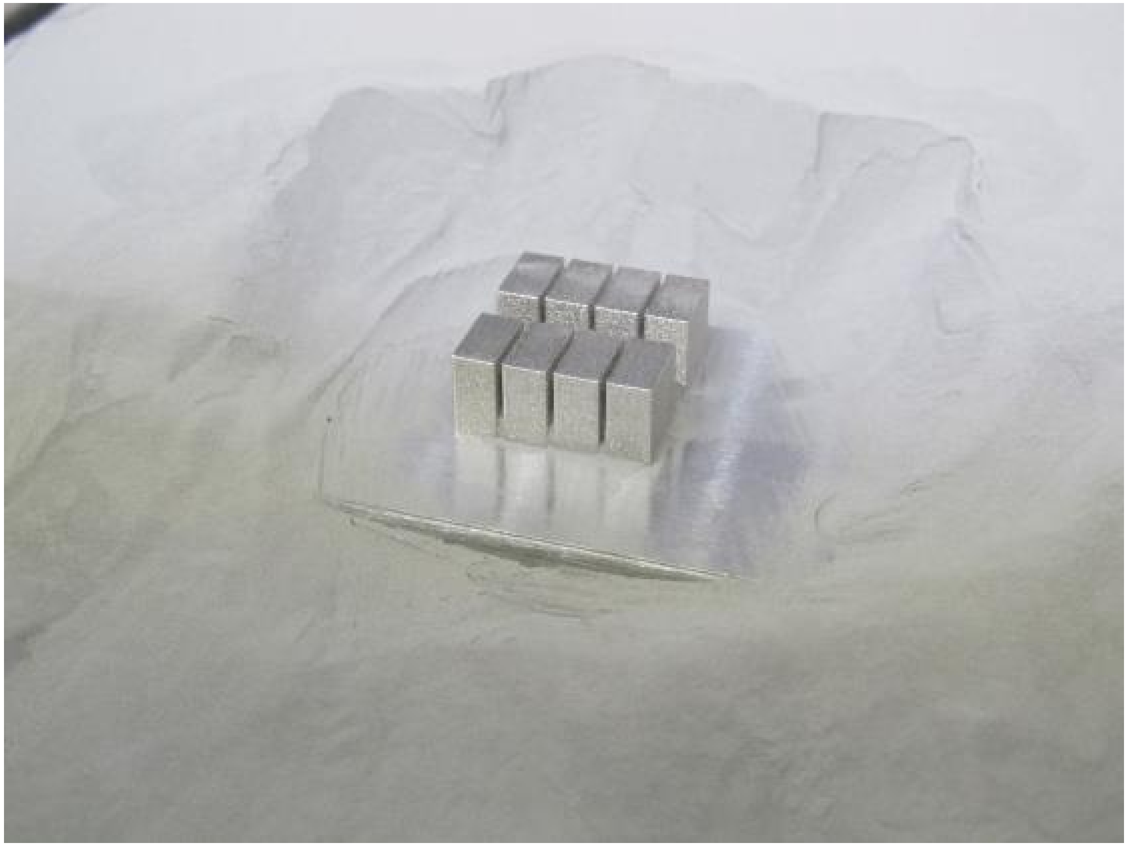
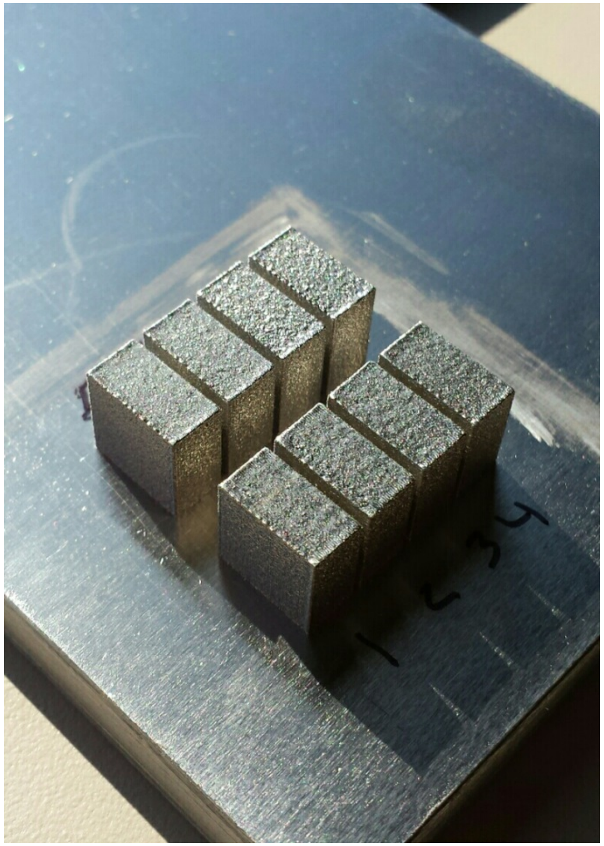
Production of Eight 5x10x10mm Prisms





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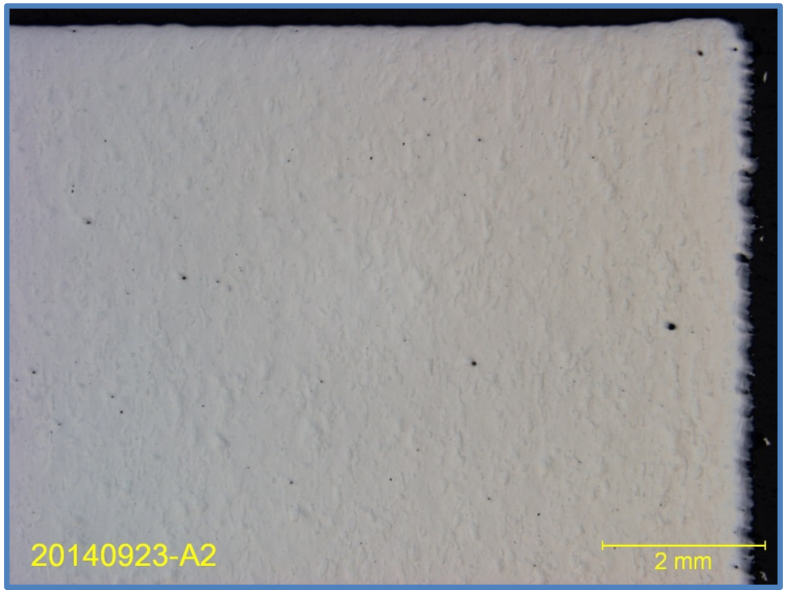
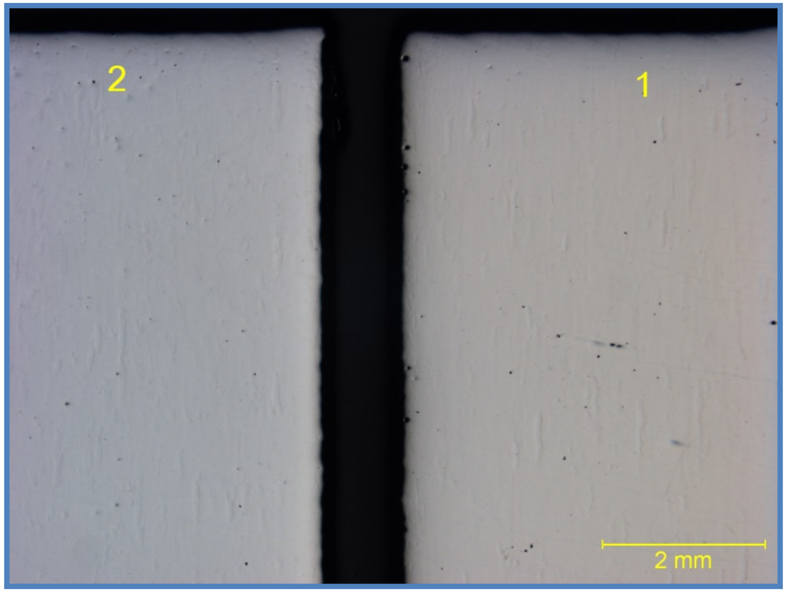
Equivalent Material Established



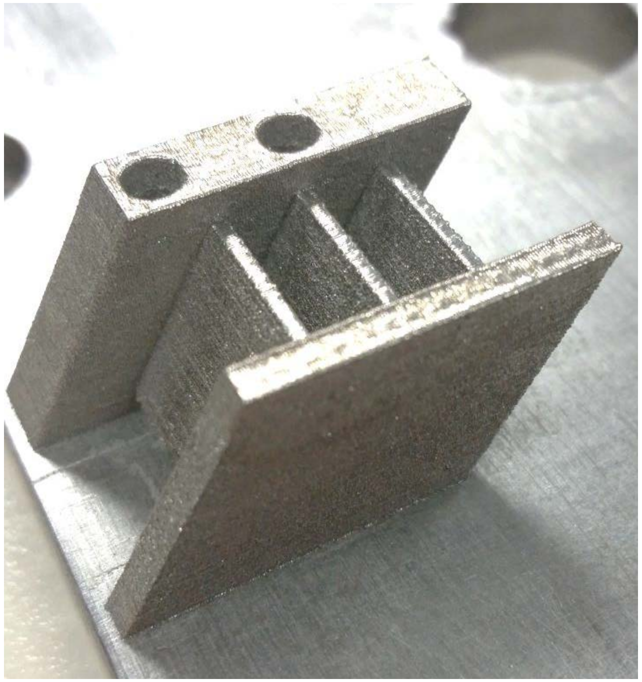
Inconel 625 on EOS Machine



Inconel 625 on Sensor Test Bed

Open Architecture System

- Complete control over toolpath generation; restricted to simple shapes.
- Control of laser power, travel speed, position of beam
- Triggering of sensors and tracking of X,Y position of beam (to track sensor data)
- Open access to the beam delivery path



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Local and Global Sensors

Integrate Sensors Into Sensor Test Bed

↓

Develop Defect-Generating Build Matrix

↓

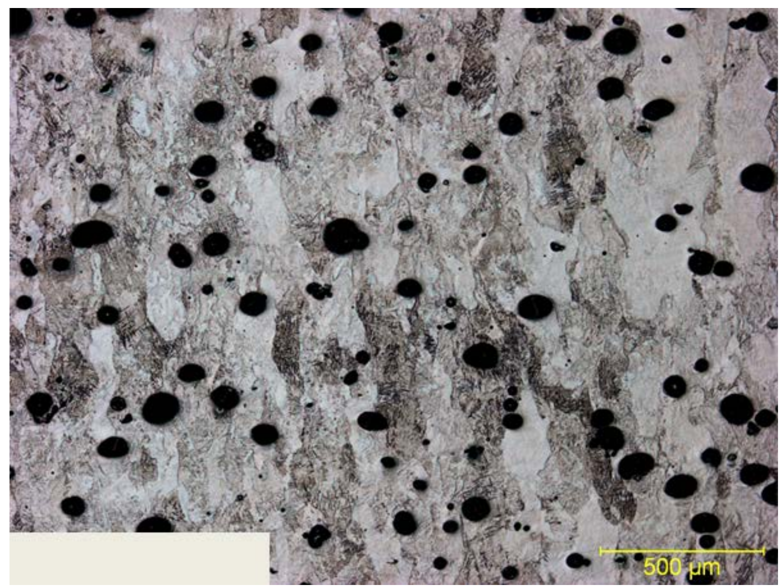
Evaluate Sensors Across Build Matrix

↓

Enhance Sensor Quality Signals

Defect Detection Goals

Metric	Threshold	Objective	Unit of Measure
Geometric Defect Detection	25 µm	10 µm	50% of geometric deviations of XX size
Volumetric Defects	250 µm	100 µm	50% of defects of XX size



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Sensors Employed

Local Sensors

- Photodetector
- Spectrometer
- High Speed Video
- Two Color Optical Pyrometer

Global Sensors

- High Resolution Imaging
- Laser Line Scan
- Global Thermal

View process at point of fusion; collect information at and surrounding the melt pool.

FOV is the powder bed. Collect information before, during, and after a layer is scanned.

Sensor Matrix

Process Observation	Sensor	Defect Type					
		Process Deviation	Distortion	Geometry	Bed Flatness	Metallurgical	Volumetric Defects
Local	High Speed Video	Defect Generation Understanding					
	Thermal Imaging					X	X
Global	High Resolution Imaging		X	X	X		
	Laser Line Scanner		X	X	X		
	Thermal Imaging					X	X
	Photogrammetry (UNCC)		X	X			
	Projection Moiré (UNCC)		X	X	X		

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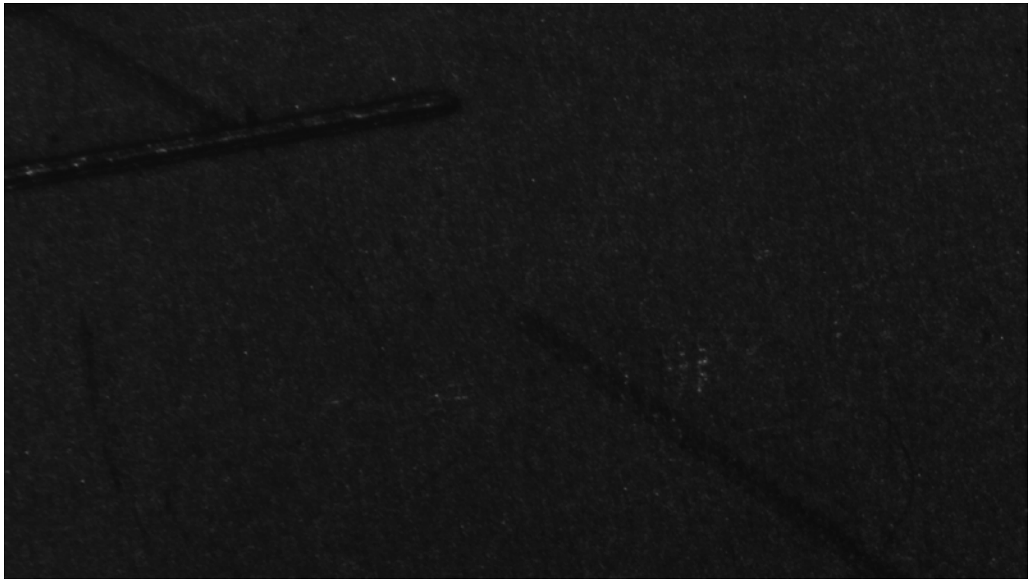
Local Techniques: High Speed Video

<u>Objective</u>: Identify defect formation, melt pool characteristics; process understanding

<u>Details:</u>

- **Bead on Plate; 40mm line; 1000FPS; laser 200W; speed: 200mm/s**



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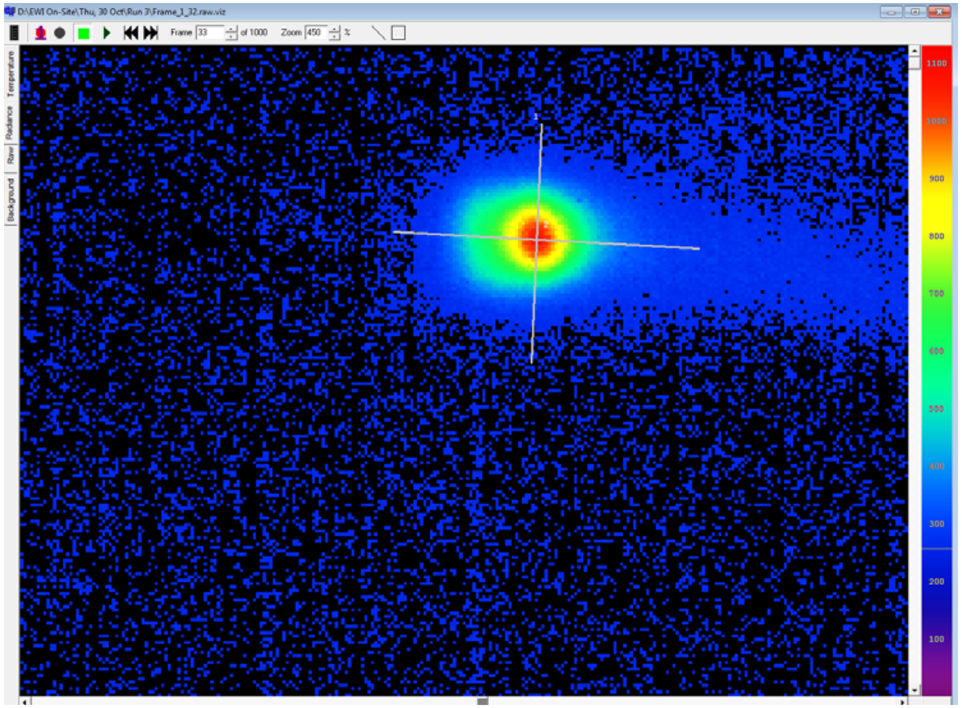
Local Sensor: Thermal Imager

- **Sensor installed on optical table and aligned with on-axis signal**
- **Sensor details:**
  - **Model**: Stratonics, IR
  - **Frame rate**: 1000 fps
  - **Exposure**: 100 us
  - **FOV**: 4.6 x 1.9 mm
  - **Resolution**: 6.8 um/pixel
- **Investigated melt pool behavior over artificial defective regions**
- **Investigated melt pool shape and size with varying parameters**



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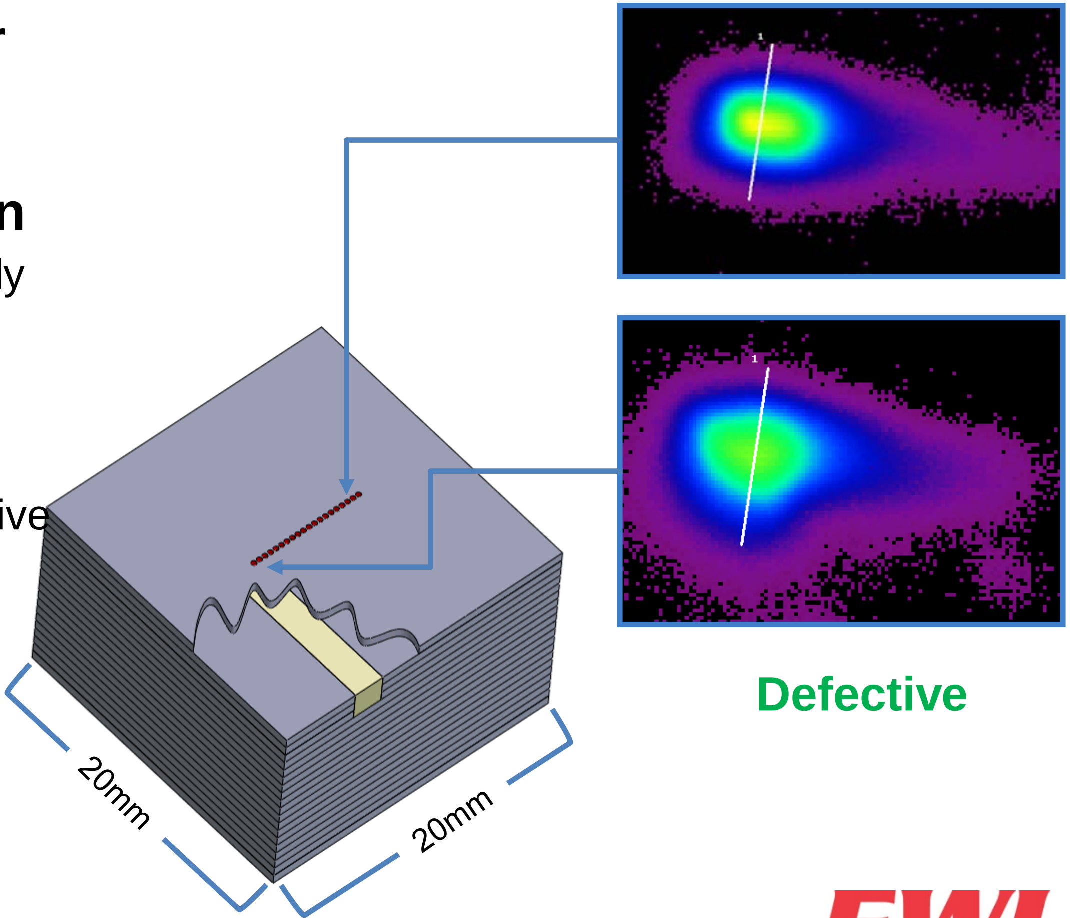
Local Sensor: Thermal Imager

- **Introduced a rectangular volume of unfused powder to the build and observed melt pool variation when processing over this region**
  - Melt pool seems to be extremely stable when processing over melted and re-solidified build material
  - Melt pool distorts when processing over artificial defective regions



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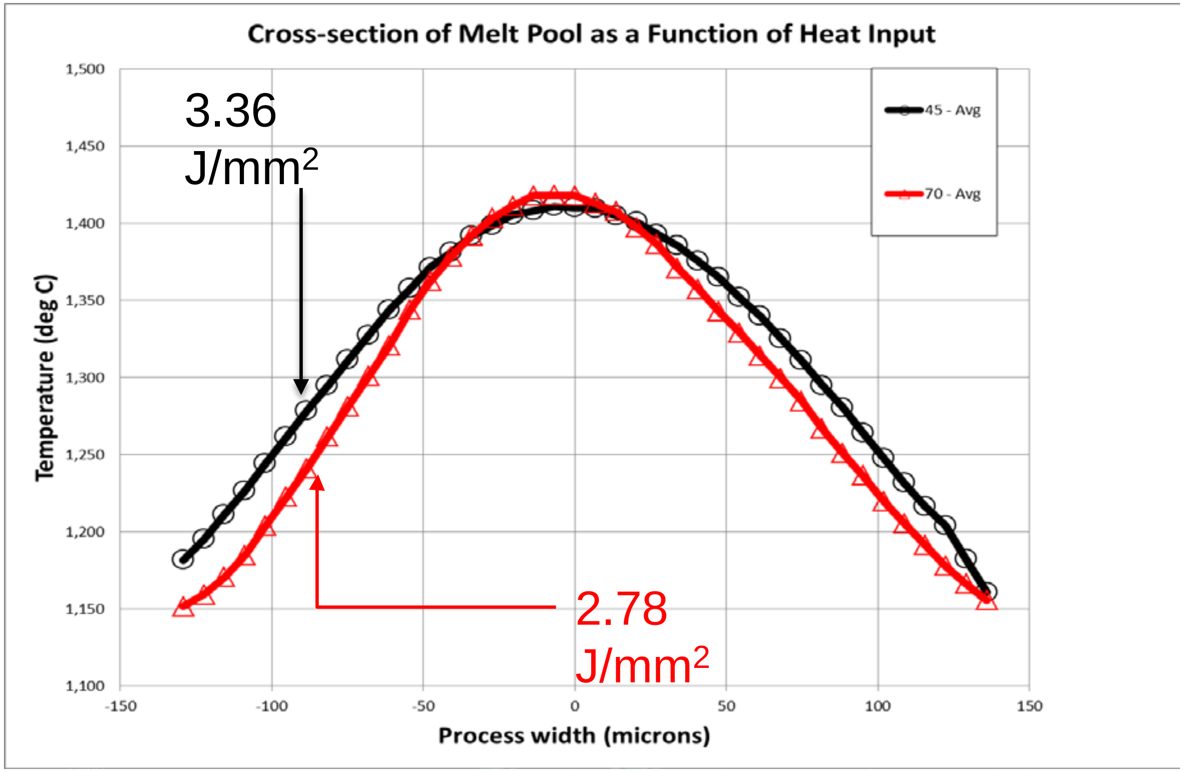
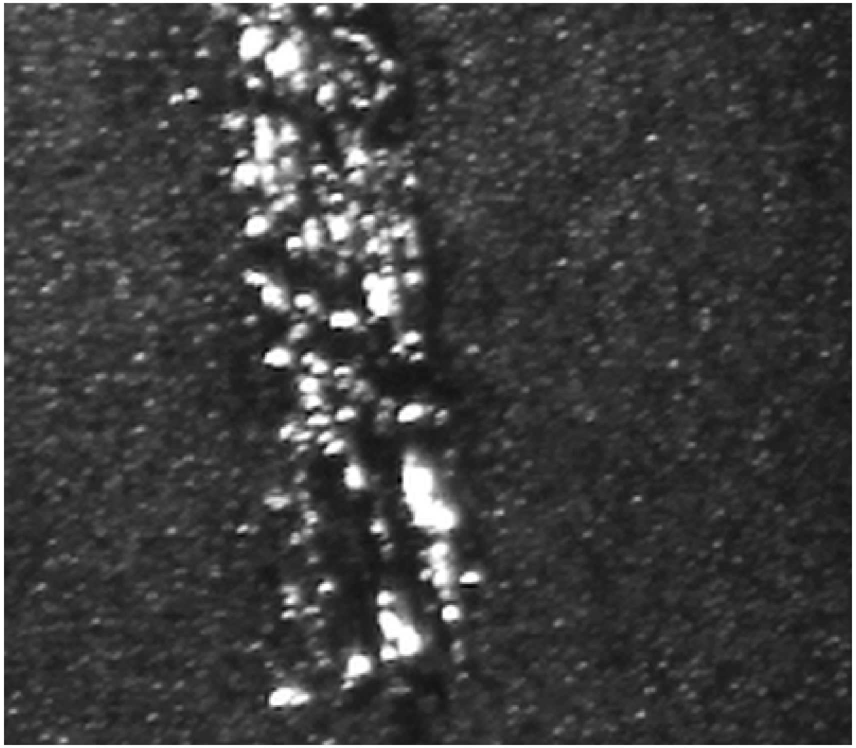
Local Sensor: Thermal Imager

- **Melt pool width increases with energy density increases are measurable**



Local Sensor: Optical Imager

- **Sensor is installed on optical table and aligned with on-axis signal**
- **Sensor details:**
  - **Model**: IDT Vision, NX7-S2
  - **Frame rate**: 1000 fps
  - **Exposure**: 20 us
  - **FOV**: 11.4 x 6.4 mm
  - **Resolution**: 5.9 um/pixel
- **Early images showed promise but required higher illumination levels**
- **High luminosity LED spot lights have been configured and tested**
- **Currently focal plane issues are plaguing the results**
- **Analysis software complete to measure melt pool size and shape**



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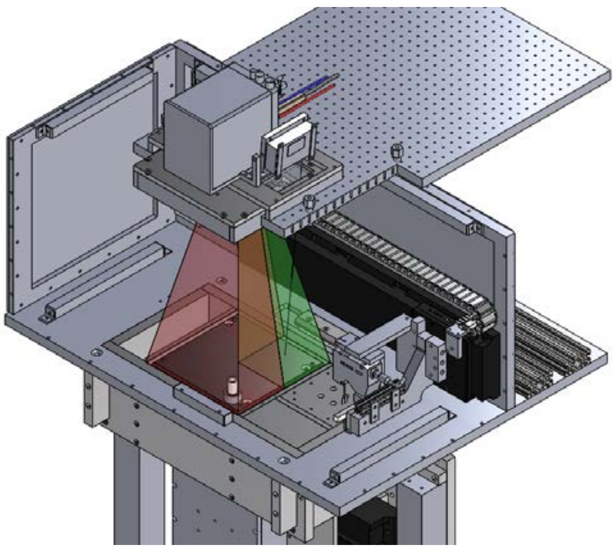
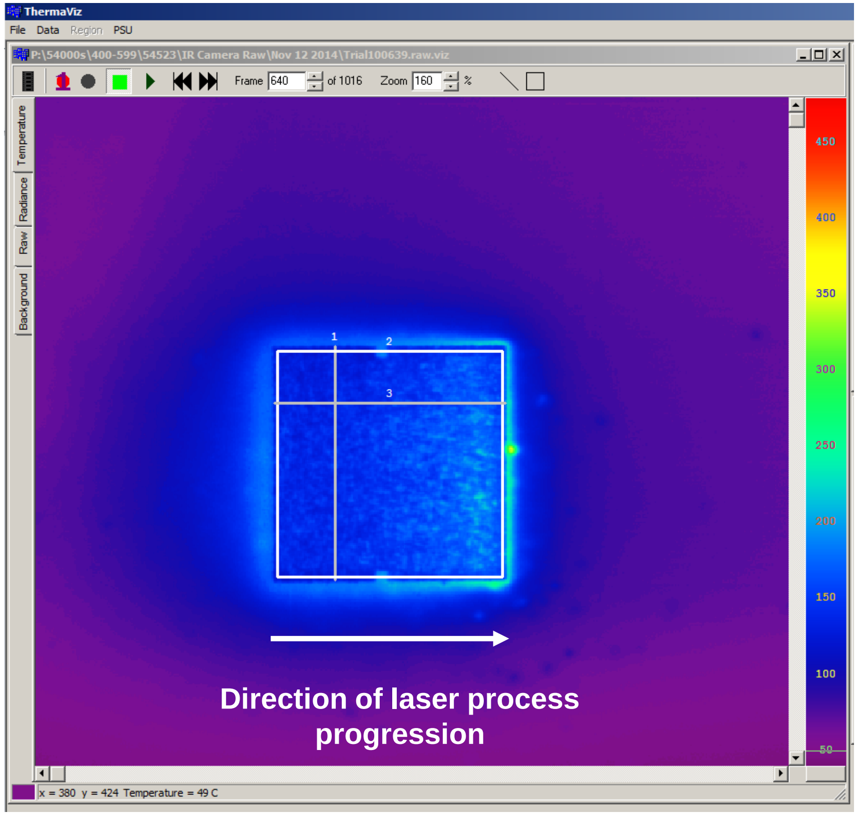
Global Sensor: Thermal Imager

- **Camera is installed over the top side viewing port**
- **Sensor details:**
  - **Model**: Stratonics, ThermaViz
  - **Frame rate**: 10 fps
  - **Exposure**: 10 ms
  - **FOV**: 83.2 x 83.2 mm
  - **Resolution**: 130 um/pixel





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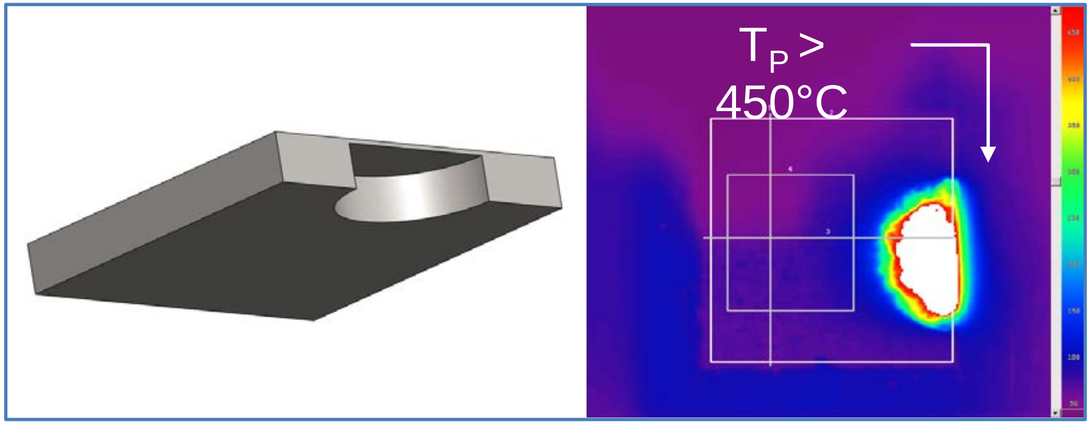
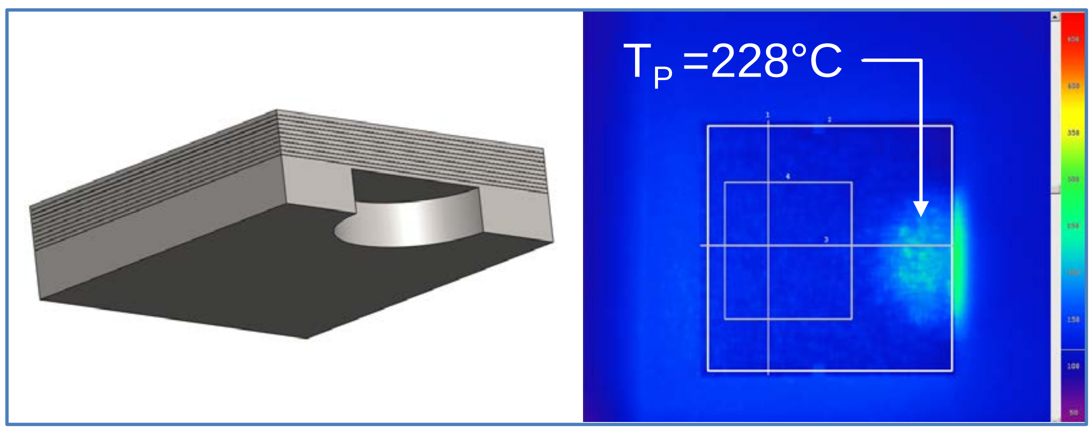
Global Sensor: Thermal Imager



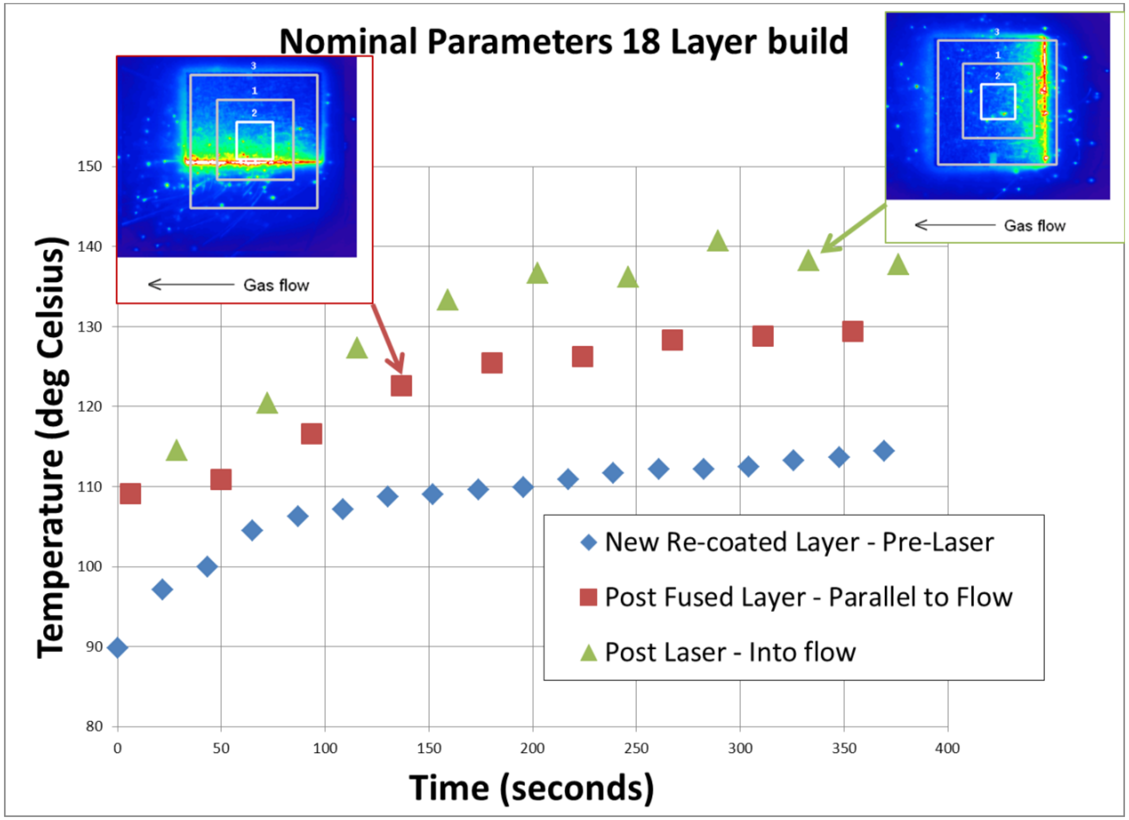
Layer 1

Layer 10



Global Sensor: Thermal Imager

- **Observed a difference in cooling when traversing the laser progression parallel to gas flow versus normal to gas flow**



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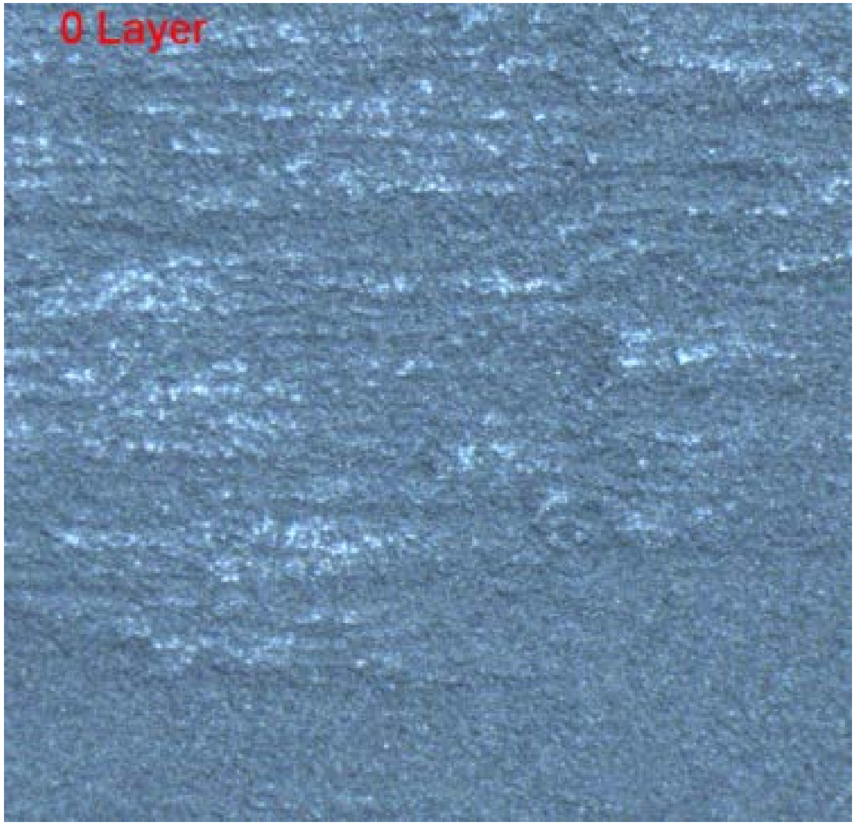
Global Sensor: Optical Imager

- **Camera is installed over the top side viewing port**
- **Sensor details:**
  - **Model**: PointGrey, Flea3
  - **Resolution**: 17.7 um/pixel
  - **FOV**: 70x40 mm
- **Images are taken after each layer is processed**
- **Software algorithms have been written to take key measurements on the build layer**
- **Limited analysis has been performed to date**



Global Sensor: Laser Profiler

- **Sensor is installed on the recoater arm**
- **Sensor details:**
  - **Model**: Keyence LJ-V7060 laser line scanner
  - **Line width**: 15 mm
  - **Resolution (width)**: 20 um
  - **Resolution (height)**: 16 um

Laser Scanned Data

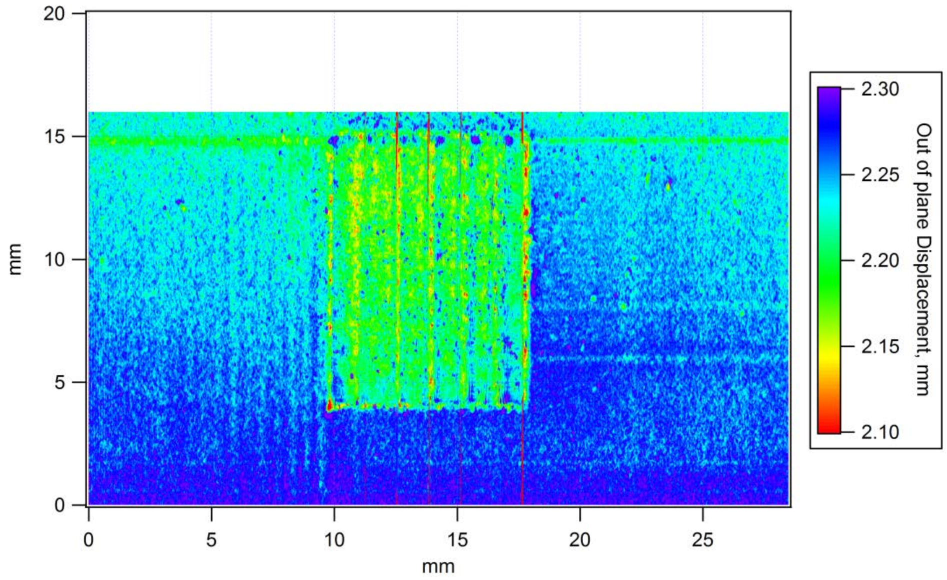
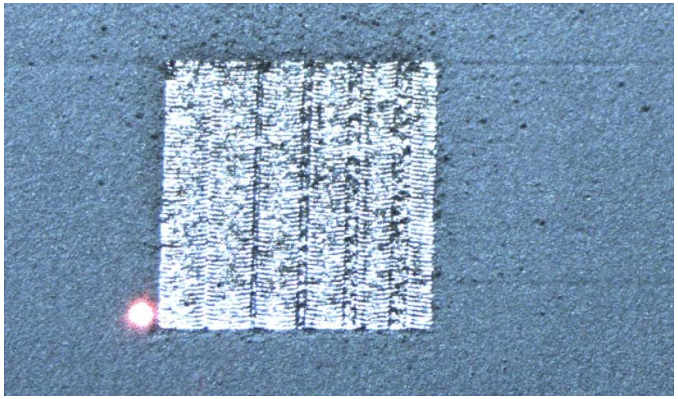


Image Scan

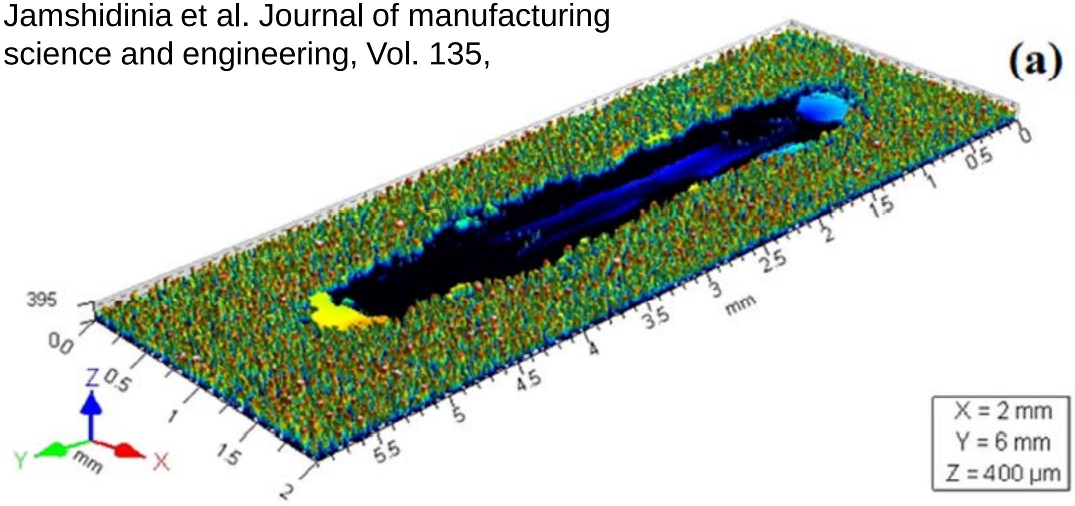


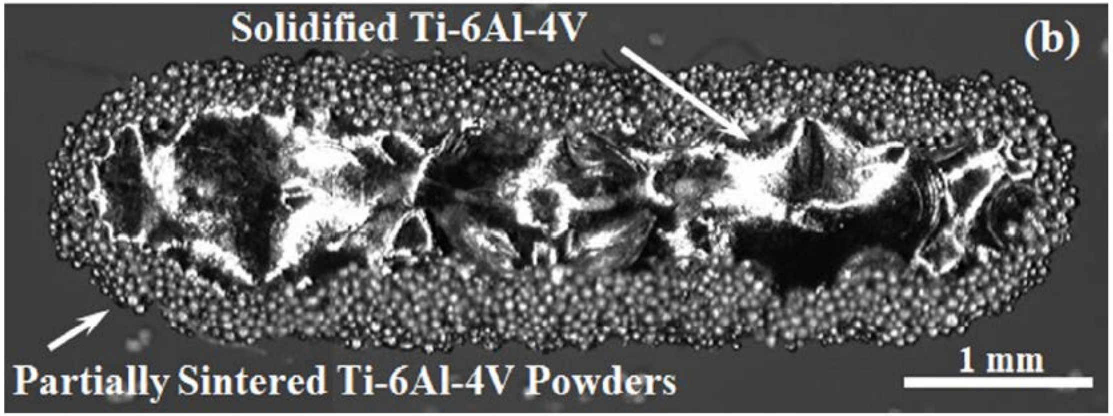
Sensing Helps Numerical Modeling

1. **Validate CFD model**
2. **Validate thermal model**
3. **Validate mechanical model**

Sensing Helps Validate Fluid Flow Predictions

Jamshidinia et al. Journal of manufacturing science and engineering, Vol. 135,





- **Computational fluid dynamics (CFD) can be used to predict the fluid flow in the molten pool.**
- **Optical images can be used to validate the CFD predictions to improve the fundamental understanding of additive manufacturing process.**

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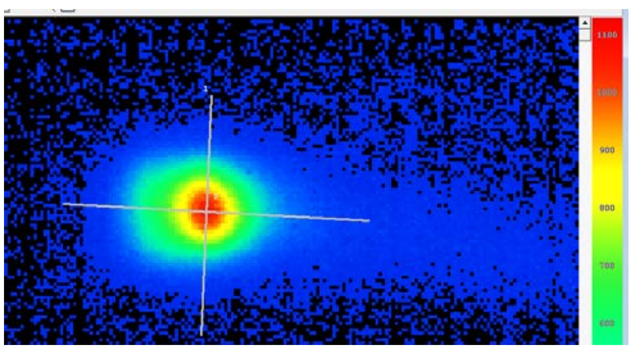
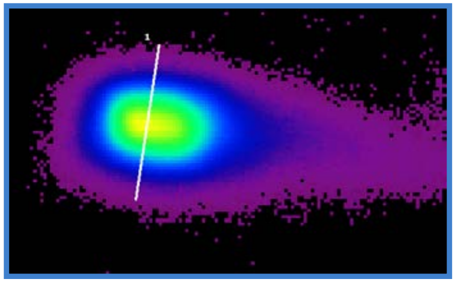
Sensing Helps Validate Temperature Prediction

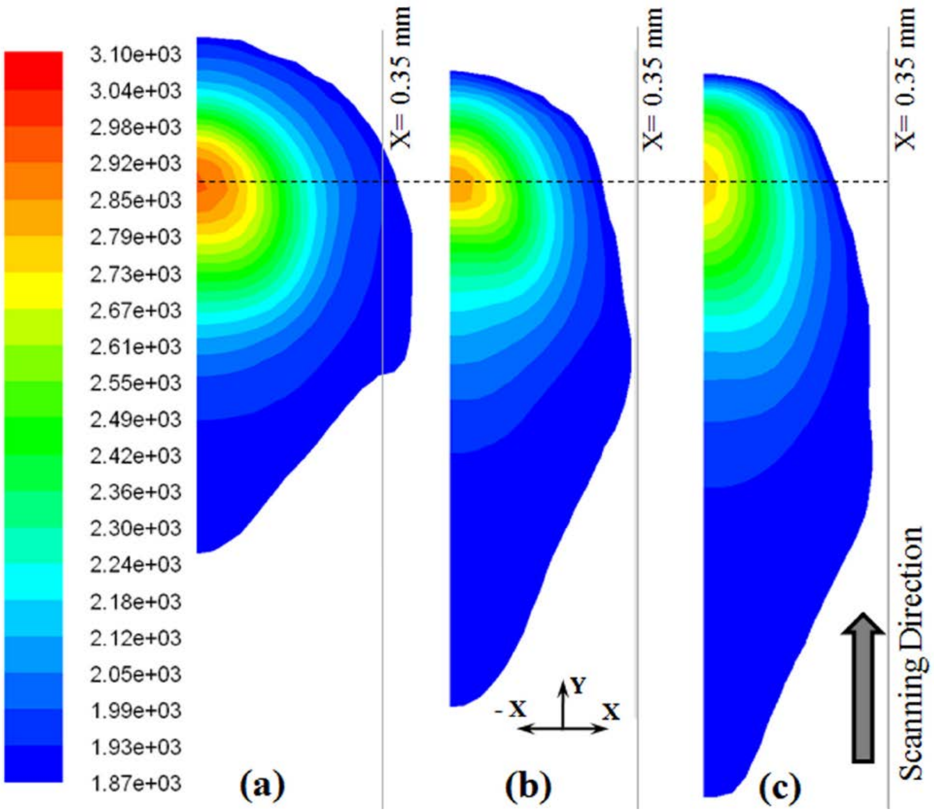
Thermal images can be used to validate numerical thermal model predictions of temperature.

Thermal images





Numerical model predicted temperature distributions



Scanning speed: (a) 100mm/s; (b) 300mm/s; (c) 500mm/s

Jamshidinia et al. Journal of manufacturing science and engineering, Vol. 135,

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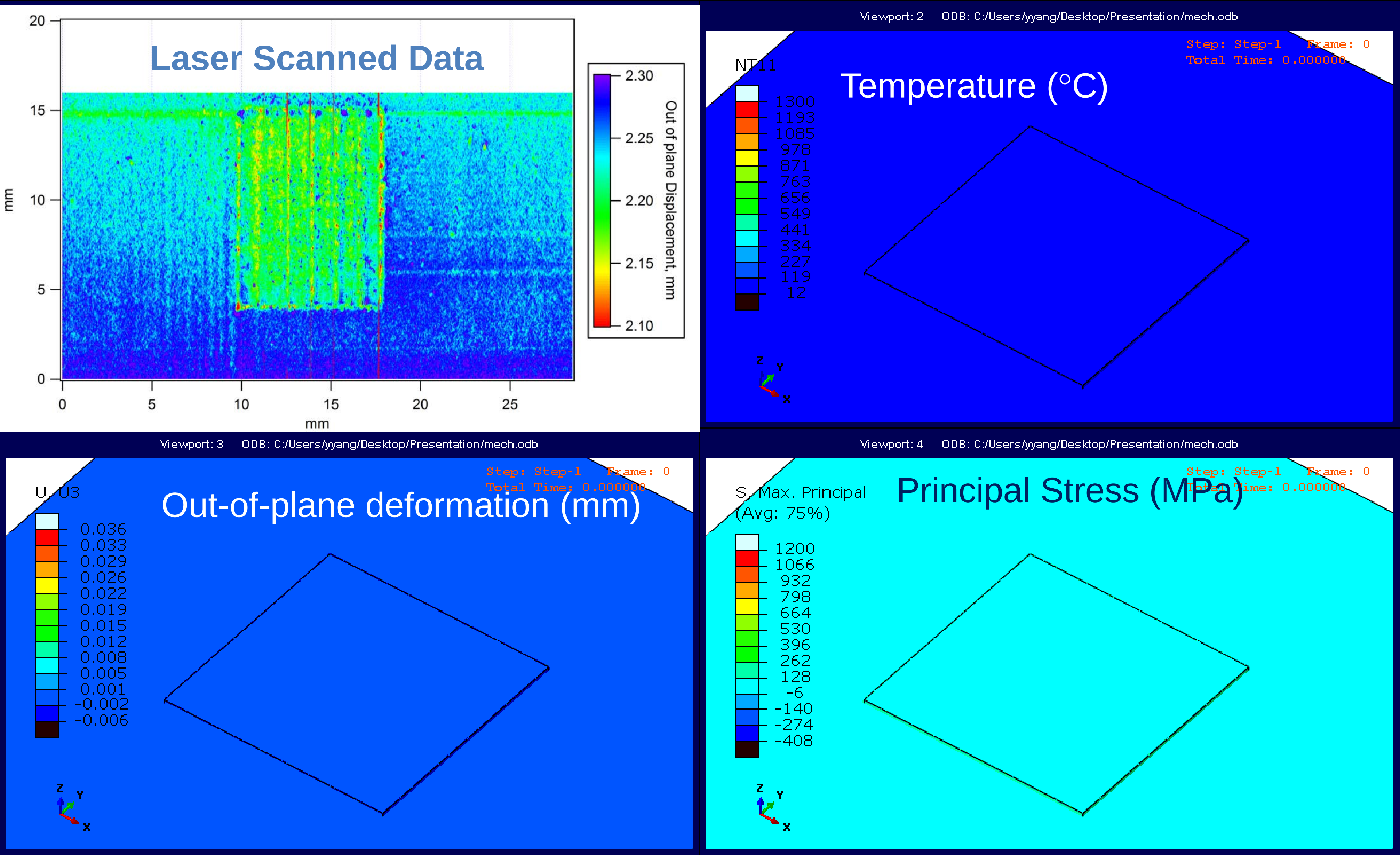
Sensing Helps Validate Mechanical Model: Temperature, Stress, and Deformation



Sensing Development Status

1. **Local sensors**
2. **Global sensors**
3. **Technical gaps**

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Local Sensor Progress to Date

- **Currently collecting data at ~10% of desire rate (once every 10 melt pools)**
- **Thermal: High resolution imaging of the melt pool; Currently operating in single-color mode due to software issues.**
- **Visual: High speed video taken; balancing illumination and focus issues.**
- **Spectrometer: Slow response time of COT sensors; overall intensity dependencies; limited analysis of line sensitivity**
- **Photodetector: Could prove useful if spectral lines can be related to defects.**

Global Sensor Progress to Date

- **Collecting data every layer.**
- **Thermal: Promising results. Large embedded defects can clearly be seen; may be masked when overhangs are present.**
- **Visual: Machine vision promising; requires algorithm development**
- **Laser Line scanner: Similar to machine vision**

Technical gaps

- **Producing Known Defects and Evaluate All sensors against these defects**

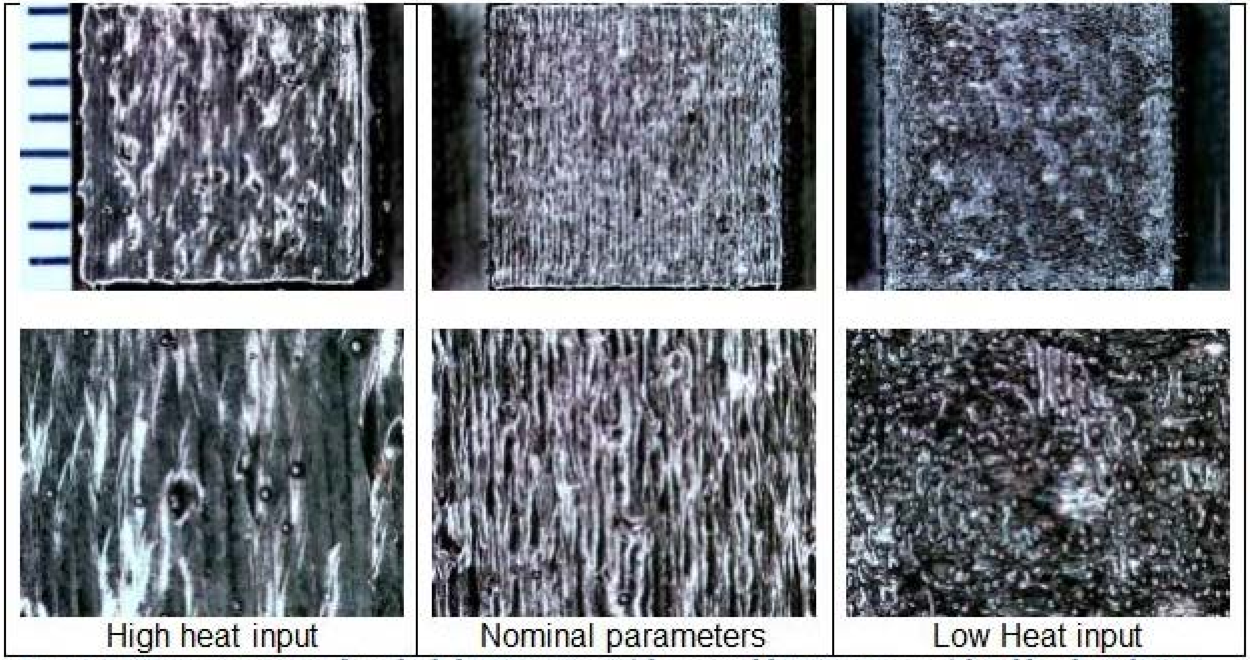
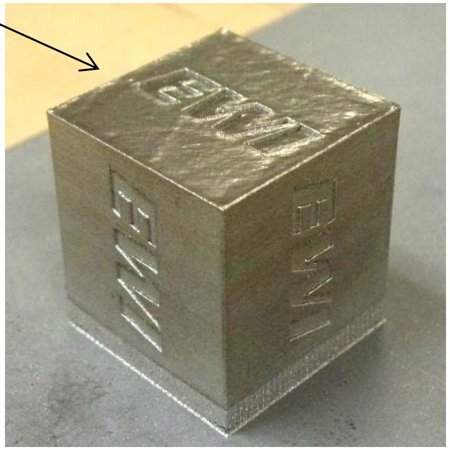


Figure 1: Steroscope images from high (370W, 384mm/s), nominal (289W, 960 mm/s) and low heat (116W, 1536 mm/s) input coupons.

Technical Gaps

BIG Challenge = BIG Data

- **throughput, processing/distillation, go/no-go, storage**
  - Global Imaging with 10MP camera: 9.6 GB
  - Local sensing: measurement every beam width >80M data points



Summary

- There is more to 3D Printing than the process…
- Treat AM like any other manufacturing process.
- Quality Control and in process sensing will be necessary to move 3DP to AM.
- Developing a flexible sensor test bed for L-PBF and evaluating candidate sensor techniques for in-process monitoring.
- Unique opportunity to inspect layer by layer

Questions

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