In-Process Sensing of Laser Powder Bed Fusion Additive Manufacturing


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A Workshop on Predictive Theoretical and Computational Approaches for Additive Manufacturing
Keck Center, Room K-100
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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

- Conventional material production steps are tightly monitored and controlled to ensure quality.

- AM is Materials Creation...directly into a functional part.
Why is In-Process Monitoring Needed?

- 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

1-inch L-PBF Cube

5 miles of weld
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
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
Develop a L-PBF Test Bed

1. Design and fabricate test bed
2. Evaluate the test bed
Design and Fabricate Test Bed

- **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
Production of Eight 5x10x10mm Prisms
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
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

<table>
<thead>
<tr>
<th>Metric</th>
<th>Threshold</th>
<th>Objective</th>
<th>Unit of Measure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geometric Defect Detection</td>
<td>25 µm</td>
<td>10 µm</td>
<td>50% of geometric deviations of XX size</td>
</tr>
<tr>
<td>Volumetric Defects</td>
<td>250 µm</td>
<td>100 µm</td>
<td>50% of defects of XX size</td>
</tr>
</tbody>
</table>
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

<table>
<thead>
<tr>
<th>Process Observation</th>
<th>Sensor</th>
<th>Defect Type</th>
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</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Process Deviation</td>
</tr>
<tr>
<td>Local</td>
<td>High Speed Video</td>
<td>Defect Generation Understanding</td>
</tr>
<tr>
<td></td>
<td>Thermal Imaging</td>
<td></td>
</tr>
<tr>
<td></td>
<td>High Resolution Imaging</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td>Laser Line Scanner</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td>Thermal Imaging</td>
<td></td>
</tr>
<tr>
<td>Global</td>
<td>Photogrammetry (UNCC)</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td>Projection Moiré (UNCC)</td>
<td>X</td>
</tr>
</tbody>
</table>
Local Techniques: High Speed Video

Objective: Identify defect formation, melt pool characteristics; process understanding

Details:
- Bead on Plate; 40mm line; 1000FPS; laser 200W; speed: 200mm/s
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
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.
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
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
Global Sensor: Thermal Imager

- Observed a difference in cooling when traversing the laser progression parallel to gas flow versus normal to gas flow.
Global Sensor: Optical Imager

- Camera is installed over the top side viewing port

Sensor details:
- **Model**: PointGrey, Flea3
- **Resolution**: 17.7 µm/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
Sensing Helps Numerical Modeling

1. Validate CFD model
2. Validate thermal model
3. Validate mechanical model
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.
Thermal images can be used to validate numerical thermal model predictions of temperature.

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

Laser Scanned Data

Temperature (°C)

Out-of-plane deformation (mm)

Principal Stress (MPa)
Sensing Development Status

1. Local sensors
2. Global sensors
3. Technical gaps
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: Stereoscope images from high (370W, 384 mm/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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Modeling and Simulation

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