Update on NIST MSAM In-Process Sensing

AMC Summer Meeting, EWI

July 16, 2015

Paul Boulware,
Applications Engineer
Outline

- **Project introduction**
  - Explanation of need
  - Project team
  - Project objectives
- **Sensor test bed**
- **Sensor evaluation**
  - Global sensors
  - Local sensors
  - Passive sensors
- **Remaining challenges**
Conventional vs. Additive

- Conventional material production steps are tightly monitored and controlled to ensure quality
- AM is materials creation of a functional part from the ground up
Need For In-Process Monitoring?

- Current mechanisms of quality control:
  - Open loop; dependent on good process development and engineering expertise
  - Post-process inspection acts as a source of validation where applicable
- 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
Measure and Certify Build Quality

In Situ Process Monitoring
Lead: EWI
- Georgia Tech
- UNC Charlotte
- Stratonics
- B6Sigma
- Paramount Industries
- GE Aviation

Non Destructive Evaluation
Lead: CTC
- North Carolina State University
- GE Aviation
- GE Inspection Technologies
- Lockheed Martin
- Pratt & Whitney

Certification Standards
Lead: University of Louisville
- Carnegie Mellon University
- University of Texas El Paso
- Penn State University
- GE Aviation
- Northrop Grumman
- Boeing
- Stryker
- Harvest Technologies
- Solid Concepts

Other Collaborators
- Oak Ridge National Laboratory
- Lawrence Livermore National Laboratory
- Imaginetics
- M7 Technologies
- Ingersoll Machine Tools

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In-Process Monitoring Team

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Lance Cronley (Design)

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Masouhmeh Aminzadeh
Thomas Kurfess

Jim Williams
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 in-process sensing techniques on a L-PBF sensor test bed with respect to potential defect-inducing conditions.

Deliverables:
1. Design, fabricate, assemble, and runoff a sensor test bed to be used for evaluating a diverse set of quality monitoring techniques.
2. Evaluation of different quality monitoring techniques with respect to defect formation and defect-inducing conditions.

Project Benefits:
- Evaluation of various sensor capabilities in an open forum/format.
- Identify potential roadblocks for sensor integration.
- Provide fundamental input for potential control systems.
Fabricate, Build, & Runoff Test Bed

**Hardware**
- Completed safety checklist and operating procedures
- Checked positional axes to be within 10um
- 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

**Equivalency Confirmed**
- Similar defect levels as EOS M280
- Use same speed as EOS
- 960 mm/s, 289W, 0.09mm hatch
Processing Video
Production of Comparison Prisms

5x10x10mm
Equivalent Material Established

Inconel 625 on EOS Machine

Inconel 625 on Sensor Test Bed
Open Architecture System

- 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
- Restricted to simple shapes
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

- Monitoring hierarchy:
  - KPP’s (before, during, and after)
  - Local material-process signal interactions
  - Global material-process signal interactions
  - Passive signals
Local Sensors: Thermal Imager

- Thermal Melt Pool Imager
- Optical Melt Pool Imager
- Photodetector
- Spectrometer
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 μm/pixel
- Investigated melt pool behavior over artificial defective regions
- Investigated melt pool shape and size with varying parameters
Local Sensor: Thermal Imager

- Introduced a rectangular volume of unfused power 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 resolidified build material
  - Melt pool distorts when processing over artificial defective regions
Local Sensors: Optical Imager

- Thermal Melt Pool Imager
- Optical Melt Pool Imager
- Photodetector
- Spectrometer
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
Local Sensors: Light Interrogation

- Thermal Melt Pool Imager
- Optical Melt Pool Imager
- Photodetector
- Spectrometer
Local Sensor: Light Interrogation

- Sensors are installed on optical table and aligned with on-axis signal
- Photodetector details:
  - Model: Thor Labs, PDA36A
  - Range: 350-1100 nm
  - Gain: 40dB
- Spectrometer details:
  - Model: Ocean Optics, HR2000+
  - Exposure: 1 ms
  - Range: 200-1100 nm
- Looking for indication lines with defect formation

640nm sensitive to oxygen
Local Sensor: Status

- **Thermal:**
  - Acquiring a thermal image of the melt pool every 1-mm at 960-mm/s
  - Able to see abnormal melt pool size and shape variance with defect-inducing conditions
  - Currently operating in single-color mode due to software issues

- **Visual:**
  - Illumination techniques operating in sync with camera shutter
  - Focus issues have been identified through the optics
  - Acquired images still need more light and better filtering

- **Spectrometer:**
  - Calibrated and aligned sensor
  - Able to see general signal variance with process parameter variation
  - Need to collect and perform analysis on data throughout defect build

- **Photodetector:**
  - Need to collect and perform analysis on data throughout defect build
  - Value depends on the output of the spectrometer analysis
Global Sensor: Thermal Imager

- Thermal Build Area Imager
- Optical Build Area Imager
- Laser Profilometer
- Fringe Projection
Global Sensor: Thermal Imager

- Camera is installed over the top side viewing port
- **Sensor details:**
  - **Model:** Stratonics, ThermaViz
  - **Frame rate:** 30 fps
  - **Exposure:** 10 ms
  - **FOV:** 83.2 x 83.2 mm
  - **Resolution:** 130 um/pixel

*Direction of laser process progression*
Global Sensor: Thermal Imager

Layer 1

TP > 450°C

Layer 10

TP = 228°C
Observed a difference in cooling when traversing the laser progression parallel to gas flow versus normal to gas flow.
Global Sensor: Optical Imager

- Thermal Build Area Imager
- Optical Build Area Imager
- Laser Profilometer
- Fringe Projection
Global Sensor: Optical Imager

- Camera is installed over the top side viewing port
- **Sensor details:**
  - **Model:** Point Grey, 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: Optical Imager

- Unfused cutout
- Unfused area
- Trough from recoater arm
Global Sensor: Laser Profilometer

- Thermal Build Area Imager
- Optical Build Area Imager
- Laser Profilometer
- Fringe Projection
Global Sensor: Laser Profilometer

- 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
Global Sensor: Fringe Projection

- Global Sensors
- Thermal Build Area Imager
- Optical Build Area Imager
- Laser Profilometer
- Fringe Projection
Global Sensor: Fringe Projection

- Fringe projection is imaged by cameras
- Images are taken after each layer
- Resulting resolutions:
  - Height, 20-um
  - Lateral, 50-um
- Similar to machine vision, algorithms are needed to identify problems
- Photogrammetry principles can be applied to enhance measurement robustness
Global Sensors: Status

- **Thermal:**
  - Able to discern geometric defects (minimum size still to be evaluated)
  - Able to discern parameter variation
  - Build area may be limited or multiple images may need to be taken

- **Visual:**
  - Able to discern geometric defects (minimum size still to be evaluated)
  - Able to discern recoating irregularities (e.g. poor spread)
  - Sensor size, optics, and position need to be optimized for each application
  - Build area may be limited or multiple images may need to be taken

- **Laser Profilometer:**
  - Build material is not an ideal material for laser triangulation (light loss)
  - Geometric defects can be discerned to a certain degree
  - COTS systems do not provide the necessary scan width and resolution

- **Fringe Projection**
  - Able to discern geometric defects (minimum size still to be evaluated)
  - Resolution is limiting
Remaining Challenges: Defects

- Developing controllable defect-inducing parameters
- Three test builds:
  - General parameter variation
  - Geometric variation
  - Defect variation
Remaining Challenges: Real-Time, Big Data & Data

- **Monitor 1st, Control 2nd**
- **Real-time data processing**
  - Need to be able to perform machine vision algorithms in real-time for decision making
  - High acquisition rates (>1000 fps)
- **Sensor fusion**
  - All data is position aligned
  - Can we correlate output to get a greater confidence of quality output?
- **Data storage**
  - What data can be processed and stored?
  - What data must be stored in a raw format?
  - Ex. Global optical images: 3.6 GB
  - Ex. Local sensing: >80M data points
Questions

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EWI is the leading engineering and technology organization in North America dedicated to advanced materials joining and allied manufacturing technologies. Since 1984, EWI has provided applied research, manufacturing support, and strategic services to leaders in the aerospace, automotive, consumer products, electronics, medical, energy & chemical, government, and heavy manufacturing industries. By matching our expertise in materials joining, forming, and testing to the needs of forward-thinking manufacturers, we are successful in creating effective solutions in product design and production.

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AFFILIATES

- RealWeld Systems, Inc.
- EJ2
- EDISON INDUSTRIAL INNOVATION
- FABRISONIC
Passive Sensor: Microphone

- Sensor is installed within test bed over the processing area

- Sensor details:
  - Model: G.R.A.S, 46BE ¼” CCP
  - Type: Free Field
  - Freq. Range: 4Hz – 80kHz

- Data as been acquired for different noise events within the chamber
  - Recirculation dominates the sound signal

- Little analysis beyond visual interrogation of time domain data has been performed
Passive Sensor: Microphone

Recoater Arm Motor (No recirculation)

Recoater Arm Motor (with recirculation)
Passive Sensor: Microphone

Laser Processing (No recirculation)

Laser Processing (with recirculation)
L-PBF Process Sensing Flow Diagram

1. Process Inputs
2. Noise Factors
3. Process By-Products
4. Process Outputs
**Sensors Employed**

<table>
<thead>
<tr>
<th>Local Sensors</th>
<th>Global Sensors</th>
<th>Passive Sensors</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Photodetector</td>
<td>• High Resolution Imaging</td>
<td>• Acoustic</td>
</tr>
<tr>
<td>• Spectrometer</td>
<td>• Laser Line Scan</td>
<td>• Ultrasonics</td>
</tr>
<tr>
<td>• High Speed Video</td>
<td>• Global Thermal</td>
<td>• Laser Interferometer</td>
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<tr>
<td>• Two Color Optical Pyrometer</td>
<td>• Photogrammetry (UNCC)</td>
<td></td>
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<tr>
<td></td>
<td>• Projection Moiré System (UNCC)</td>
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## Sensor Matrix

<table>
<thead>
<tr>
<th>Process Observation</th>
<th>Sensor</th>
<th>Defect Type</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td><strong>Process Deviation</strong></td>
</tr>
<tr>
<td>Local</td>
<td>Photodetector</td>
<td>X</td>
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<tr>
<td>Spectrometer</td>
<td>X</td>
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<tr>
<td>Interferometer</td>
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</tbody>
</table>
Target Defects

- Process deviations
- Distortion
- Geometry
- Bed flatness
- Metallurgical
- Pores/Lack of Fusion/Cracking
Concept Layout of Through the Beam Sensors
Sensor Test Bed (EWI)

- Don’t limit process sensing because of constraints.
- Replicate important characteristics of the commercial process.
- Provide adequate space.
  - Avoids problem of physical and software constraints
  - EWI has experience in integration of laser scanning optics, machine development and sensor evaluation.

Test Bed

M280 Build Platform

Sensed Area of Test Bed

Scanner Origin

150 mm
125 mm
125 mm
125 mm

150 mm
150 mm
Sensor Test Bed Concept
Sensor Test Bed Current Status

- Currently performing run-off and initial process verification.
- Extensive sensor testing over next 3 months.
- Conducted preliminary sensor testing...
Local Techniques: Photodetector

Objective: Identify process anomalies from total light emission due to:
- Energy fluctuation
- Contamination

Acquisition Rate at 1000mm/s:
- Measurement every 200 µm

Why drop in signal?
Local Techniques: Spectrometer

Objective: Identify process anomalies from spectral emission due to:
- Energy fluctuation
- Contamination

Acquisition Rate at 1000mm/s:
- Measurement every 4000 µm
Local Techniques: High Speed Video

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

**Acquisition Rate at 1000mm/s:**
• Measurement every 1000 µm (up to 200 µm)

**Details:**
• Bead on Plate
• 40mm line
• 1000FPS
• 200W@200mm/s
Global Techniques: Surface Mapping

Objective: Measure distortion, part/powder boundary, bed flatness
- Measurements every layer

Resolved 200 um wide, 40 um tall tracks
Objective: Identify process stability, crack formation, recoater issues.
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
  - Variety of Local, Global, and Passive techniques