Machine Learning-based Processing of Thermal Tomography Images for Automated Quality Control of Additively Manufactured Stainless Steel and Inconel Structures

Award Number: ANL 18-15141
Award Dates: 10/2018 to 9/2021
PI: Alexander Heifetz
Team Members: Xin Zhang, Jafar Saniie (IIT), Dmitry Shribak, Sasan Bakhtiari, Boris Khaykovich (MIT NRL), Bill Cleary (Westinghouse)
Project Objectives

• Quality control of stainless steel and Inconel structures produced with laser powder bed fusion (LPBF) process for nuclear energy applications
  - Intrinsic LPBF process flaws lead to formation of pores (lack of fusion, keyhole)
  - Pores may cause thermal fatigue crack initiation
• Probability is higher for large pores near surface

Visualization of porosity in as-built AM SS316L specimen with X-ray tomography at APS. The z-axis is the build direction. 1 pixel ≈ 1 µm

M. Li, et. al., ANL/NSE-20/42 (2020)
Project Objectives

- Quality control of stainless steel and Inconel structures produced with LPBF process
  - Nondestructive imaging (detection and classification) of sub-surface pores with thermal tomography in post-manufacturing

Stack of thermography frames

FLIR x8501sc MWIR 1280x1024 at 180fps
Technical Progress/Accomplishments

• Obtained thermal tomography reconstructions for two types of calibrated defects
  - Flat bottom holes in SS316

Technical Progress/Accomplishments

- Obtained thermal tomography reconstructions for two types of calibrated defects
  - Imprinted hemispherical regions containing un-sintered powder in IN718

Technical Progress/Accomplishments

- Developed machine learning algorithms for enhancing thermography images of imprinted calibrated defects

Spatio-temporal blind source separation

- Observed thermograms
- Wavelet Transformation
- Spatial images de-noising
- Dimensionality reduction
- De-noised thermography data cube $X$
- PCA pre-processing
- Principal components
- Estimated independent sources TSI

Spatio-temporal sparse dictionary learning

- Observed thermograms
- Wavelet Transformation
- Spatial images de-noising
- Dimensionality reduction
- De-noised thermography data cube $X'$
- SVD pre-processing
- Principal components

X. Zhang, et. al., JOM 1-13 (2020)
Technical Progress/Accomplishments

- Developed machine learning algorithms for de-noising of thermal tomography reconstructions obtained with compact low-cost IR camera
  - FLIR A65sc microbolometer detector (640x512 at 30Hz)

X. Zhang, et. al., JOM 1-10 (2020)
Project Impacts

• Journal Publications
Project Impacts

• Conference Papers


Project Impacts

- **Conference Presentations**
  - Presented at *ANS Winter Meeting*, November 2019, Washington, DC.

- **Patents**
  - Submitted invention disclosure to ANL Legal Office, December 2019.

- **Involvement**
  - Wrote two NEET AMM Newsletter articles

- **Invitations**
  - Presented invited talk at Purdue University, School of Nuclear Engineering, April 2019
  - Presented invited e-talk at University of Texas, San Antonio, Department of Electrical and Computer Engineering, April 2020
  - Invited to give a talk at Georgia Tech School of Mechanical Engineering, Nuclear & Radiological Engineering Program, January 2021
Milestones and Deliverables for FY-20

- Completed all scheduled milestones
- No extensions were requested

<table>
<thead>
<tr>
<th>Milestone Title</th>
<th>Due Date</th>
<th>Status</th>
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</thead>
<tbody>
<tr>
<td>Imaging of Calibrated Defects in AM Materials</td>
<td>3/31/2020</td>
<td>Completed</td>
</tr>
<tr>
<td>Development of Compact Low-Cost System</td>
<td>8/14/2020</td>
<td>Completed</td>
</tr>
<tr>
<td>Imaging of Defects in AM Metallic Materials</td>
<td>9/15/2020</td>
<td>Completed</td>
</tr>
<tr>
<td>Second Annual Progress Report</td>
<td>9/30/2020</td>
<td>Completed</td>
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Issues and Concerns

• COVID-19 impacts
  - COVID-19 has halted our testing abilities because we could not enter the lab from mid-March to mid-August
  - Present work requirements of wearing masks and face shields cause personnel fatigue and reduce productivity
  - Mitigate by scheduling one worker in the lab at a time
Milestones and Deliverables for FY-21

<table>
<thead>
<tr>
<th>Milestone Title</th>
<th>Due date</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Performance of in-service system in imaging of defects</td>
<td>3/31/2021</td>
<td>On-time</td>
</tr>
<tr>
<td>Validation of TT imaging resolution</td>
<td>8/16/2021</td>
<td>On-time</td>
</tr>
<tr>
<td>TT system performance in NDE of defects in AM structures</td>
<td>9/15/2021</td>
<td>On-time</td>
</tr>
<tr>
<td>Final Technical Report</td>
<td>9/20/2021</td>
<td>Would like to extend to 12/31/2021</td>
</tr>
</tbody>
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- Extension of final report deadline will allow time to submit papers for publication
Milestones and Deliverables for FY-21

• Demonstration of in-service NDE
  - Planning for thermography of calibration target inside MITR during next shutdown in January 2021
  - Shipped FLIR Boson miniature IR camera and Hastelloy plate with calibrated defects to MIT
Milestones and Deliverables for FY-21

• Improve performance of lab NDE system
  - Increased flash thermal flux by replacing IR filter with Fresnel lens
    • Measured surface temperature on metallic plate ~200°C
  - Obtained extender rings for higher resolution imaging (up to 30µm/pixel)
  - Installed 3-axis micro positioner translation stages for better alignment
Milestones and Deliverables for FY-21

• Improve performance of lab NDE system
  – Select optimal set of imaging parameters (imaging resolution, frame rate)
  – Smallest detected defect in SS316 thus far is 750µm imprinted hemisphere with un-sintered powder

FLIR x8501 set to 768x768 pixels array, 268fps
Milestones and Deliverables for FY-21

• Aim to detect defects down to 50µm size
  – Upgraded x8510sc camera with microscopic IR lens with resolution up to 5µm/pixel

Demonstration of imaging resolution

IR image of TrueForm SS316 powder with mean diameter of 50µm on metallic plate

Individual powder particles are visible
Possible Areas/Industries/Programs (and Readiness) for Adoption

• Aiming to achieve TRL 3-4
• Discussed project progress with Westinghouse industrial collaborator
• Held discussions with small businesses
  – Relimetrics of Sunnyvale, CA, specializing in machine vision for quality control
  – Triton Systems of Boston, MA, specializing in materials and manufacturing
Contact Information and Questions

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