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. 1pixel ≈ 1μm
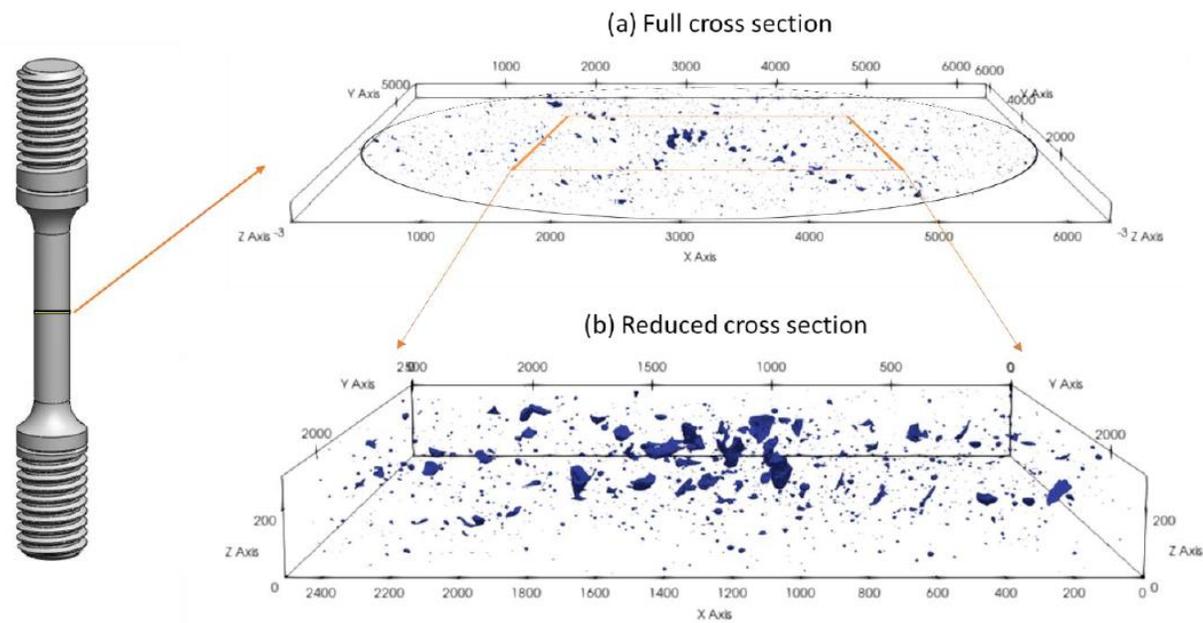
M. Li, et. al., ANL/NSE-20/42 (2020)

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
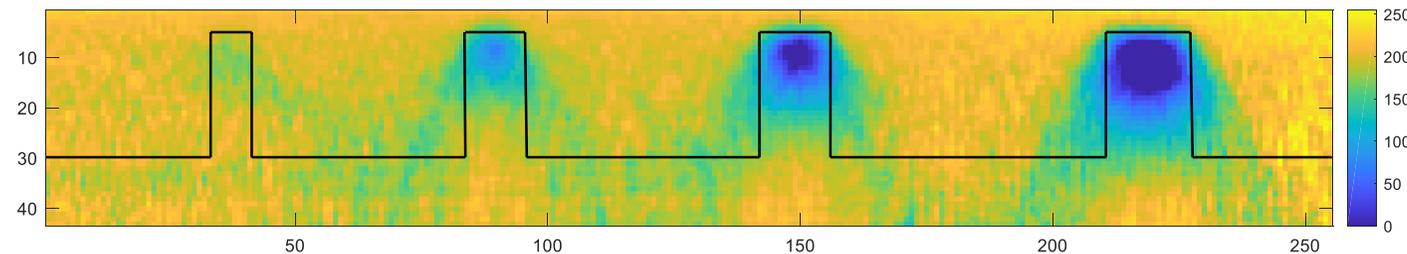

Stack of thermography frames
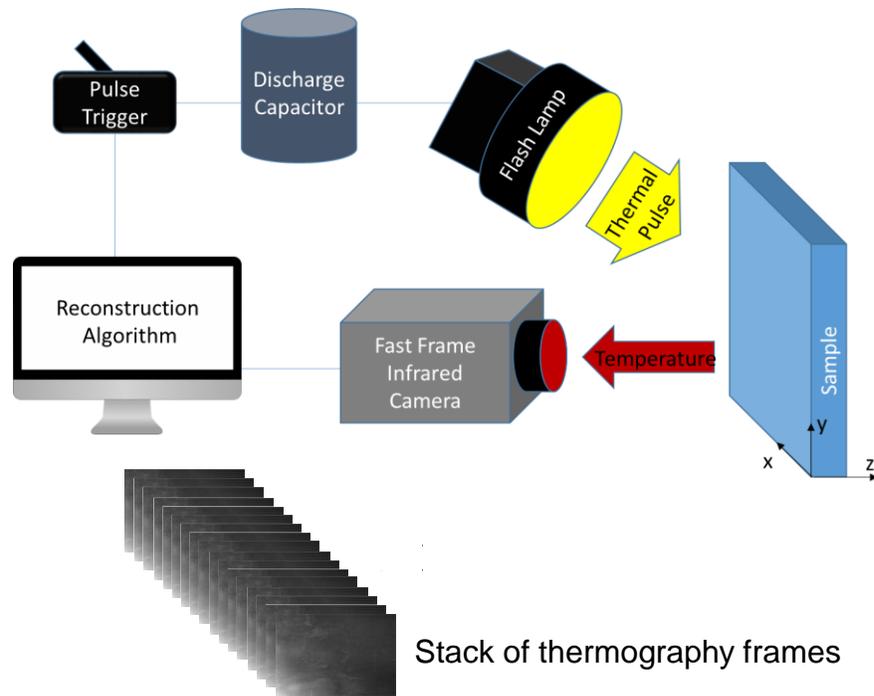
FLIR x8501sc MWIR 1280x1024 at 180fps

Technical Progress/Accomplishments

- Obtained thermal tomography reconstructions for two types of calibrated defects
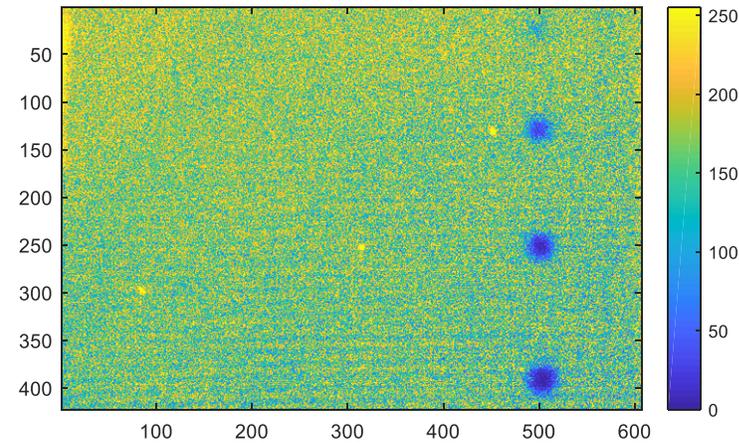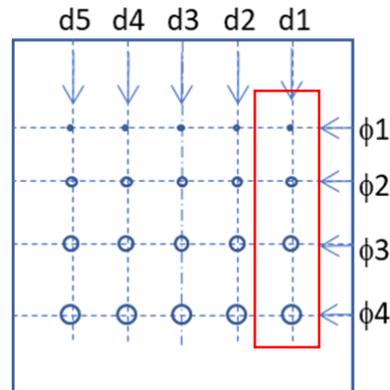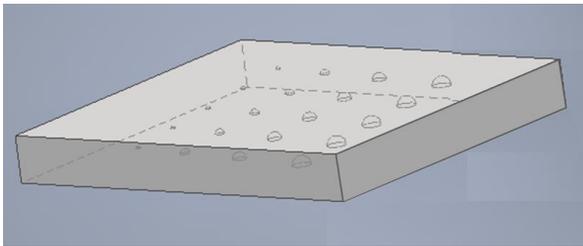 - Flat bottom holes in SS316
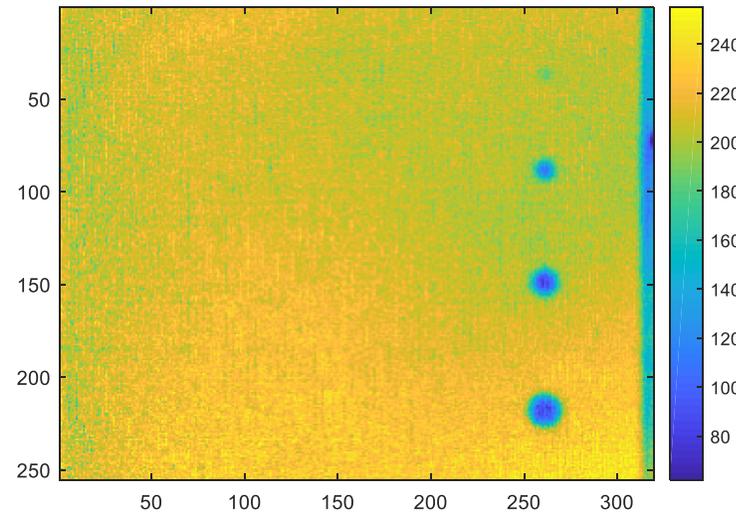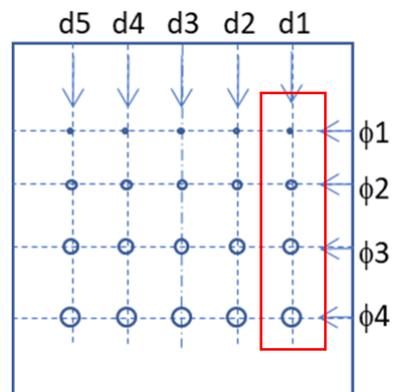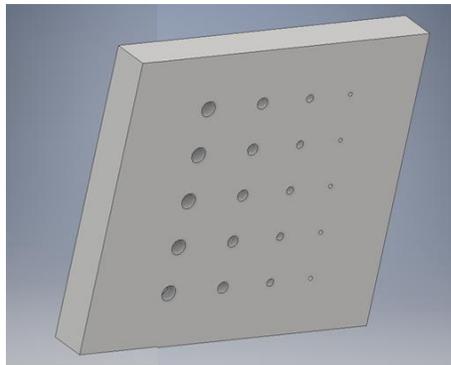
A. Heifetz, et. al. *AIP Advances* 10, 105318 (2020)

Technical Progress/Accomplishments

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

A. Heifetz, et. al. *AIP Advances* 10, 105318 (2020)
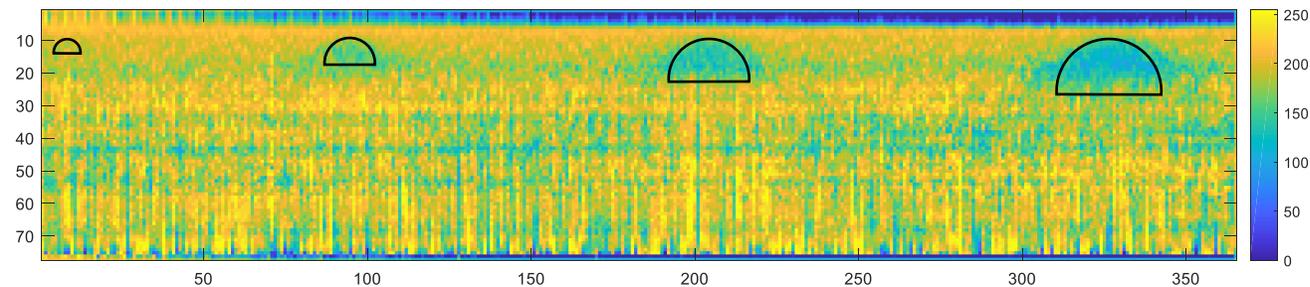
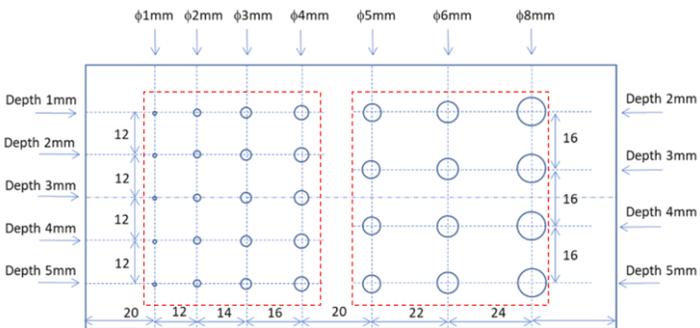# Technical Progress/Accomplishments

- Developed machine learning algorithms for enhancing thermography images of imprinted calibrated defects
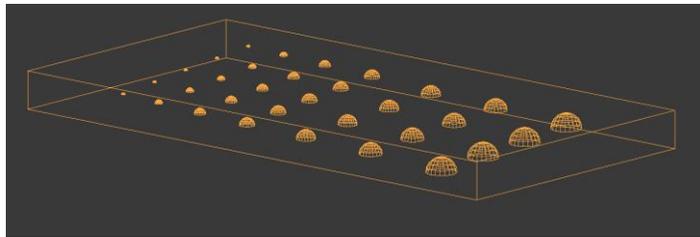
Spatio-temporal blind source separation
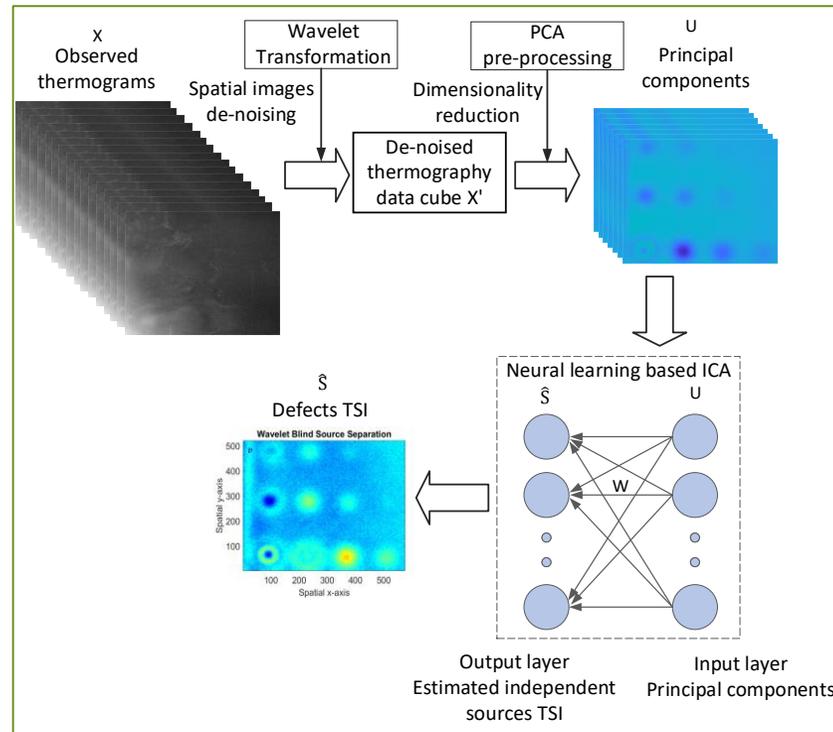
Spatio-temporal sparse dictionary learning
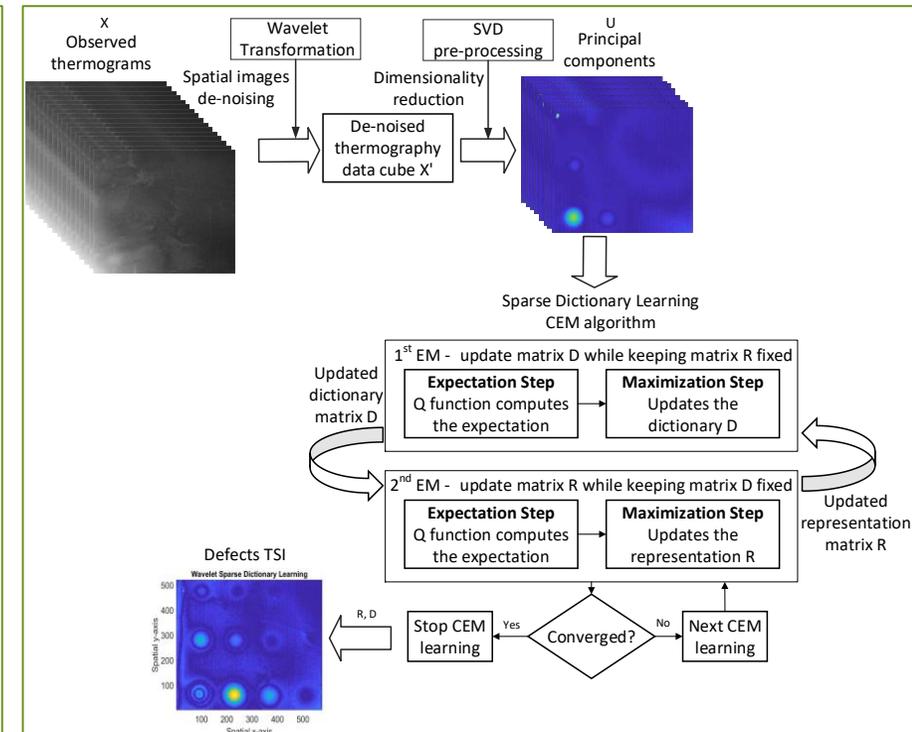
X. Zhang, et. al., *JOM* 1-13 (2020)

Advanced Methods for Manufacturing

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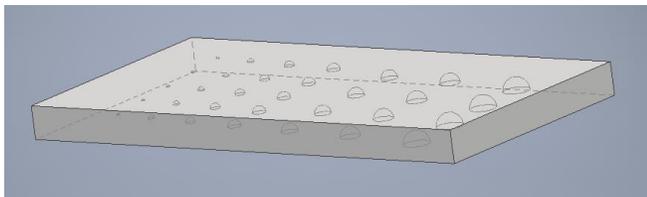
X. Zhang, et. al., *JOM* 1-10 (2020)

Project Impacts

- Journal Publications
    - A. Heifetz, D. Shribak, X. Zhang, J. Saniie, Z. Fisher, T. Liu, J.G. Sun, T. Elmer, S. Bakhtiari, W. Cleary, "Thermal Tomography 3D Imaging of Additively Manufactured Metallic Structures," *AIP Advances* 10, 105318 (2020)
    - X. Zhang, J. Saniie, W. Cleary, A. Heifetz, "Quality Control of Additively Manufactured Metallic Structures with Machine L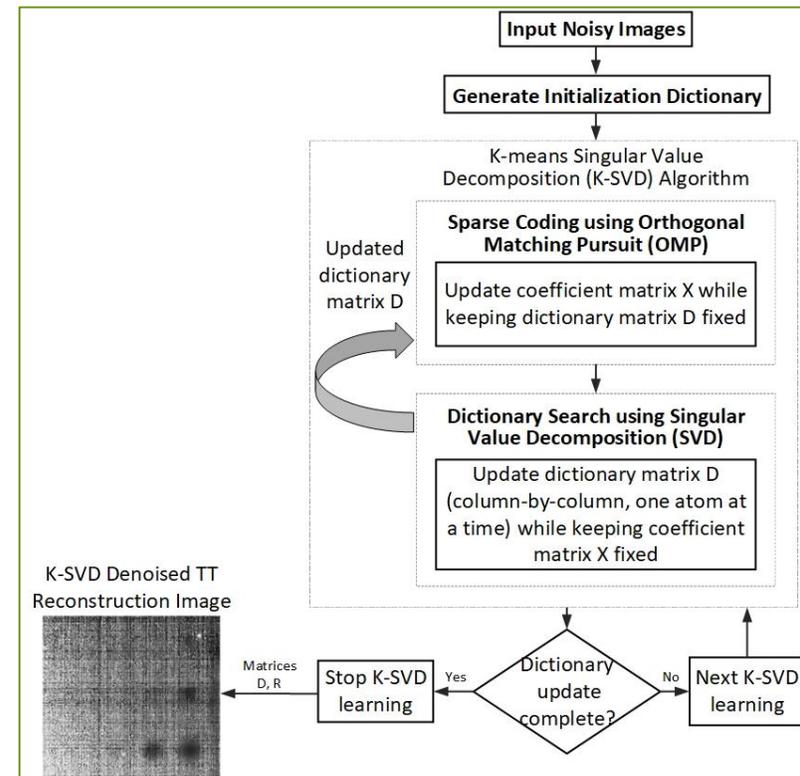earning of Thermography Images," *JOM Special Issue on Machine Learning Applications in Advanced Manufacturing Processes*, 1-13 (2020)
    - X. Zhang, J. Saniie, A. Heifetz, "Detection of Defects in Additively Manufactured Stainless Steel 316L with Compact Infrared Camera and Machine Learning Algorithms," *JOM Special Issue on Additive Manufacturing for Energy Applications*, 1-10 (2020)

Project Impacts

- ## Conference Papers
  - X. Zhang, J. Saniie, A. Heifetz, "Neural Learning Based Blind Source Separation for Detection of Material Defects in Pulsed Thermography Images, " *IEEE International Conference on Electro Information Technology* (EIT2020) (**Best Paper Award**)
  - A. Heifetz, Z. Fisher, D. Shribak, "Detection of Defects in Additively Manufactured Metals using Thermal Tomography," to appear in *Transactions of TMS 2021 Annual Meeting, special session on Additive Manufacturing for Energy Applications*
  - A. Heifetz, D. Shribak, T. Liu, T. Elmer, P. Kozak, S. Bakhtiari, B. Khaykovich, W. Cleary, "Pulsed thermal tomography nondestructive evaluation of additively manufactured reactor structural materials," *Transactions of the American Nuclear Society* 121(1), 589-591 (2019).

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

Milestone Title	Due Date	Status
Imaging of Calibrated Defects in AM Materials	3/31/2020	Completed
Development of Compact Low-Cost System	8/14/2020	Completed
Imaging of Defects in AM Metallic Materials	9/15/2020	Completed
Second Annual Progress Report	9/30/2020	Completed

Advanced Methods for Manufacturing

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

Milestone Title	Due date	Status
Performance of in-service system in imaging of defects	3/31/2021	On-time
Validation of TT imaging resolution	8/16/2021	On-time
TT system performance in NDE of defects in AM structures	9/15/2021	On-time
Final Technical Report	9/20/2021	Would like to extend to 12/31/2021

- Extension of final report deadline will allow time to submit papers for publication

AMM
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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
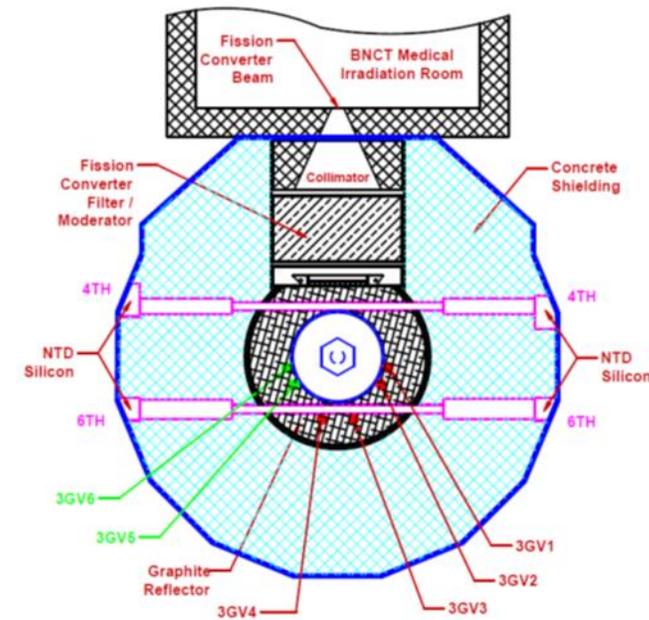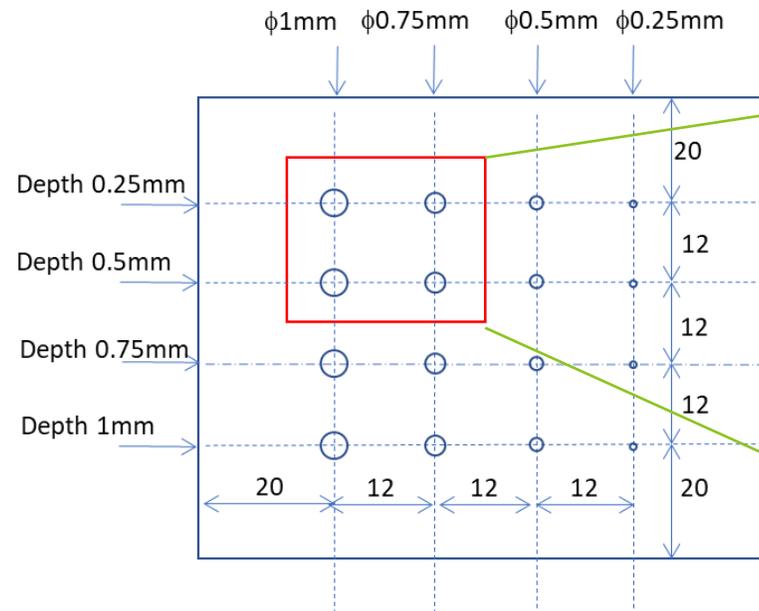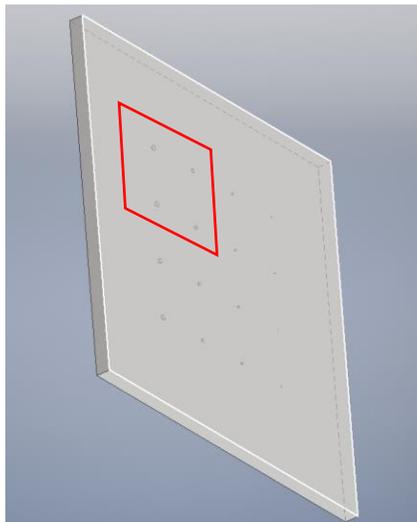
Milestones and Deliverables for FY-21

- 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

Extender ring

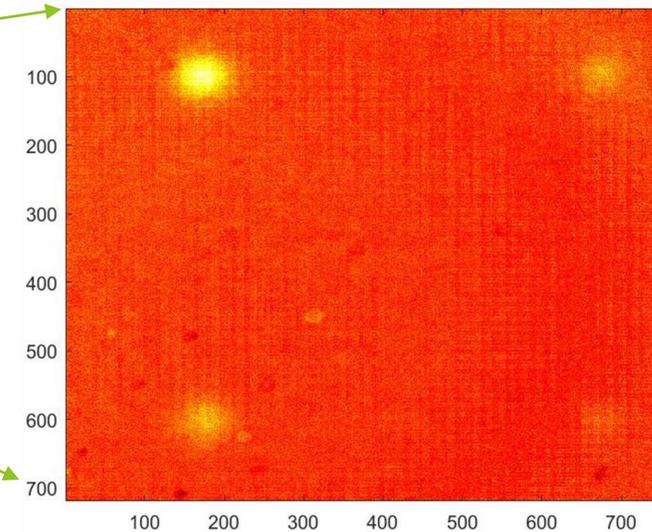Fresnel lens

3-axis translation stages
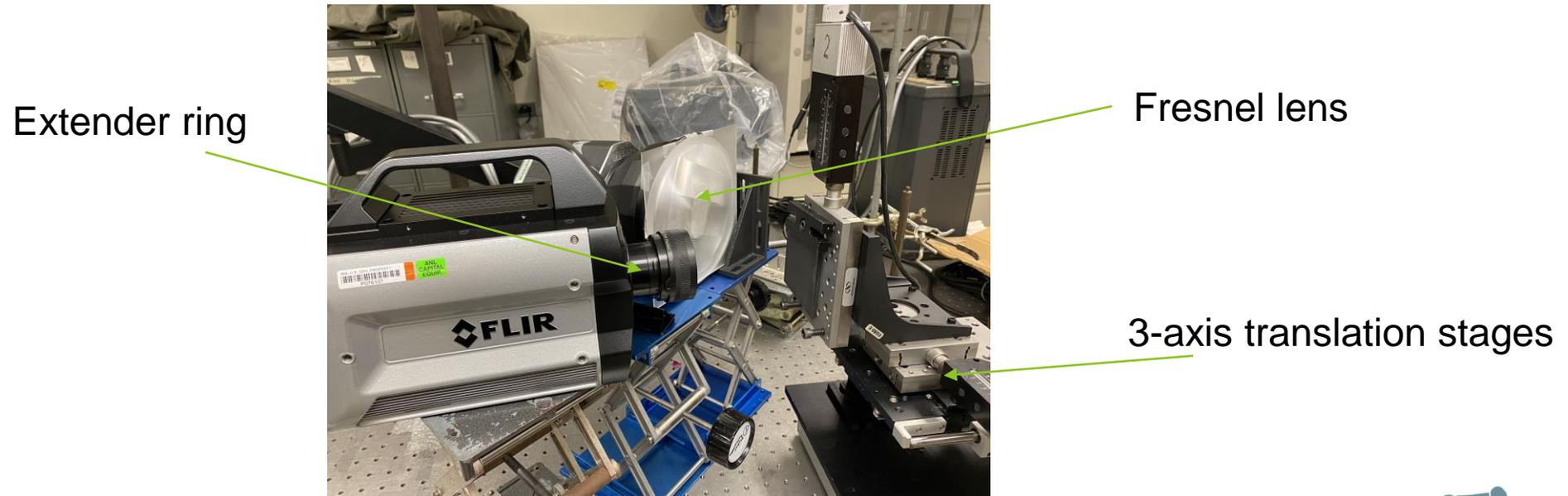
Milestones and Deliverables for FY-21

- 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
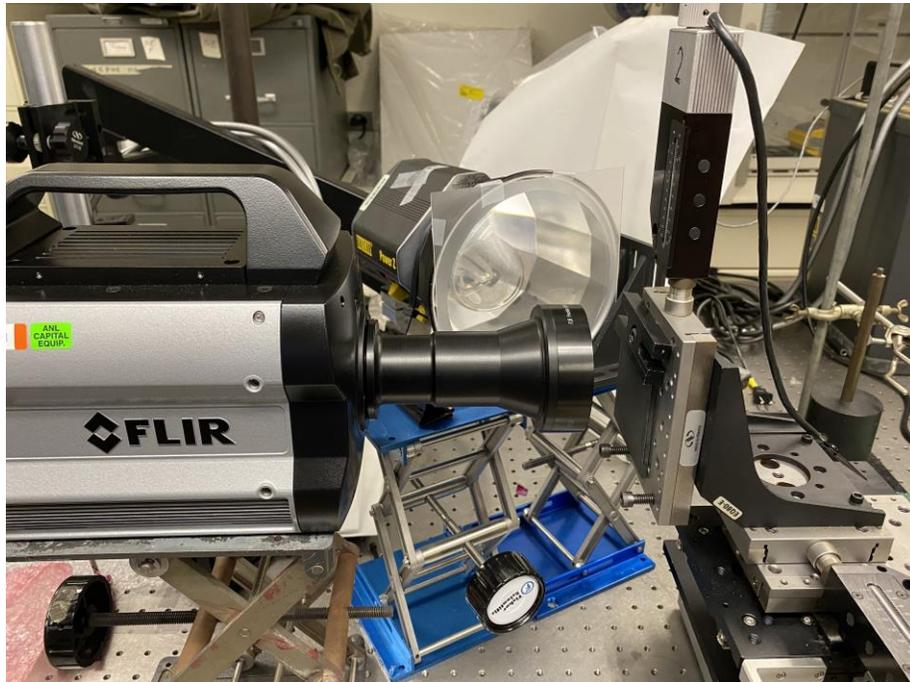

Imaged with 50mm lens, processed with NLBSS
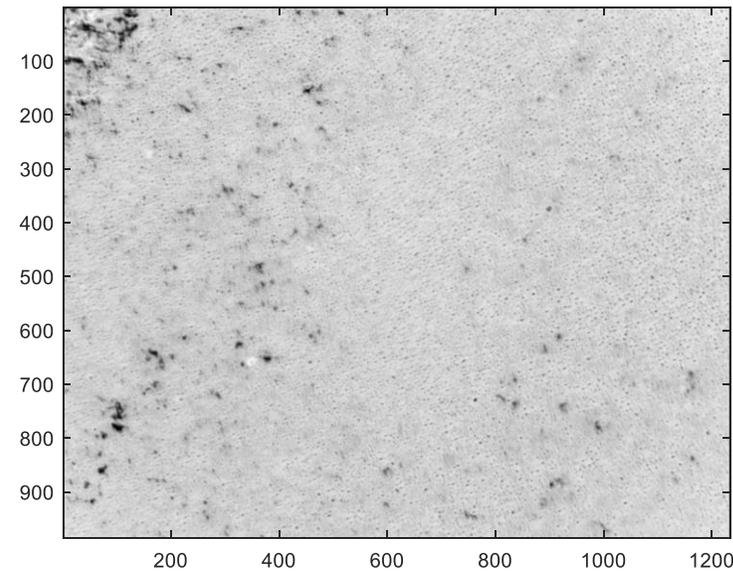
FLIR x8501 set to 768x768 pixels array, 268fps

Milestones and Deliverables for FY-21

- Aim to detect defects down to 50um 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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