NASA NDE Efforts for Additive Manufacturing

Joseph N. Zalameda

NASA Langley Research Center Hampton, VA 23681

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Outline

- NASA Office of Safety and Mission Assurance (OSMA) Efforts
- NASA Material Genome Initiative (MGI)
  - Following up effort: NASA Additive Manufacturing Structural Integrity Initiative (AMSII)
- In-Situ Techniques for Additive Manufacturing

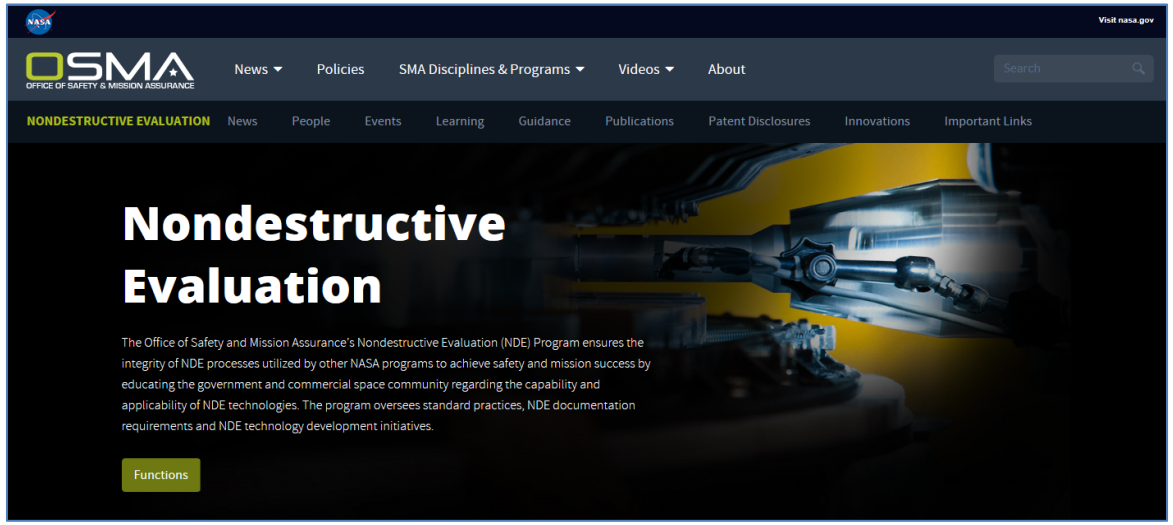
NASA Office of Safety and Mission Assurance (OSMA)

- The Office of Safety and Mission Assurance (OSMA) assures the safety and enhances the success of all NASA activities through the development, implementation and oversight of agency-wide safety, reliability, maintainability and quality assurance policies and procedures.
- OSMA disciplines and programs include: aviation safety, electrical safety, facility safety, fire protection, mishap investigation, pressure vessels and systems, orbital debris, nondestructive evaluation, reliability and maintainability…….

NASA Office of Safety and Mission Assurance (OSMA) – Nondestructive Evaluation

Nondestructive Evaluation Sciences Branch

https://demo.sma.nasa.gov/sma-disciplines/nondestructive-evaluation





NDE Certification for Additive Manufacturing

Nondestructive Evaluation Sciences Branch

Current Standard Viable Techniques

- Computed Tomography & Radiography
  - Currently NASA Gold standard
- Ultrasonic
- Eddy Current
- Penetrant

Note: Front End processing is also in work

Issues for Standard Viable Techniques

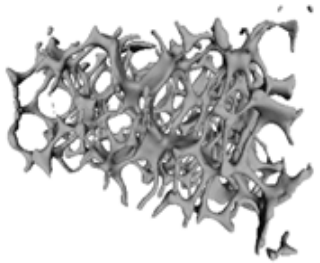
- Computed Tomography & Radiography
  - Time Prohibitive
  - Ionizing Radiation
  - Qualification of CT Systems
- Ultrasonic
  - Internal Structure Beam Steering
  - Complex Beam Paths due to geometry
- Eddy Current
  - Surface texture
  - Depth of Penetration
- Penetrant
  - Surface only

Improvement and Integration

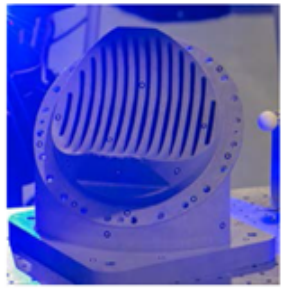
- Computed Tomography & Radiography
  - Possible Insitu-inspection and repair
  - IQI Based Certification for CT Systems
  - Certification CR and DR systems
- Ultrasonic
  - Use of beam correction algorithms
  - High fidelity modeling for sound placement
- Eddy Current
  - Spec finished parts for inspection
  - Articulated scanning techniques for better access
- Thermal
  - Insitu-Inspection and repair
  - Closed loop control for geometry and metallurgy

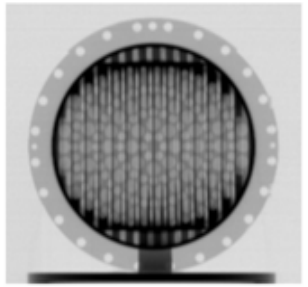
Examples





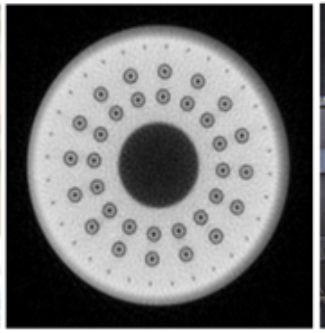
CT Ti-6-4 Metal Foam & Fabrication

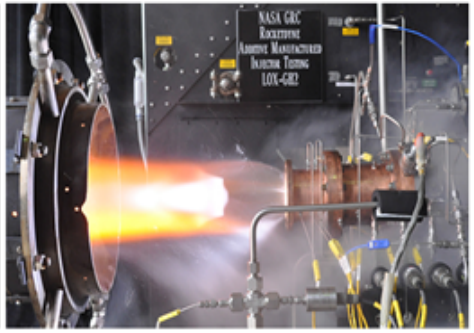




CT Pogo-Z baffles, RS-25/J2-X





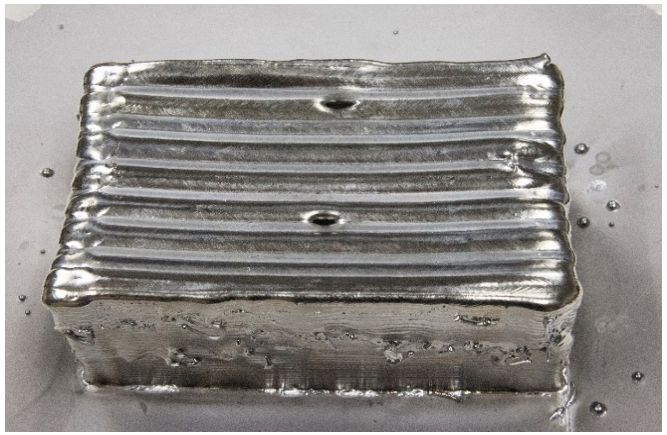


NASA\Rocketdyne GRC Additive Manufactured Rocket Injector

Investigation of Phased Array Ultrasonics on AM Material

Nondestructive Evaluation Sciences Branch

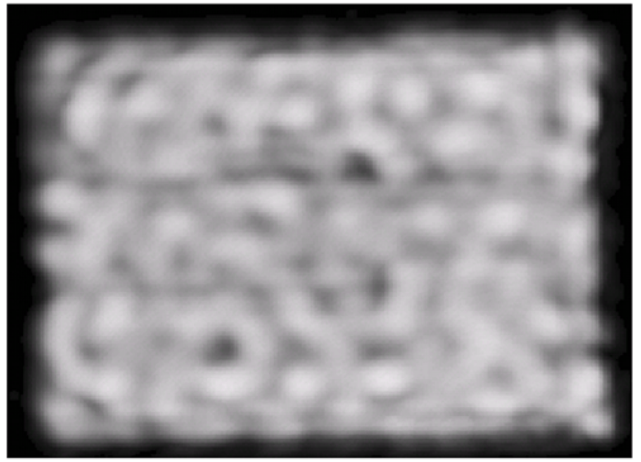
- Fabricate Phase 1 Ti 6Al-4V Electron Beam Free Form Fabrication (EBF3) AM specimen blanks
- Machine programmed flaws in some of the Phase 1 specimens
- Scan wrought Titanium step wedge block
- Set-up using dual matrix DMA probes



First Attempt - Beads separated during deposition and formed two holes approximately 2” deep – block will be inspected at JSC.

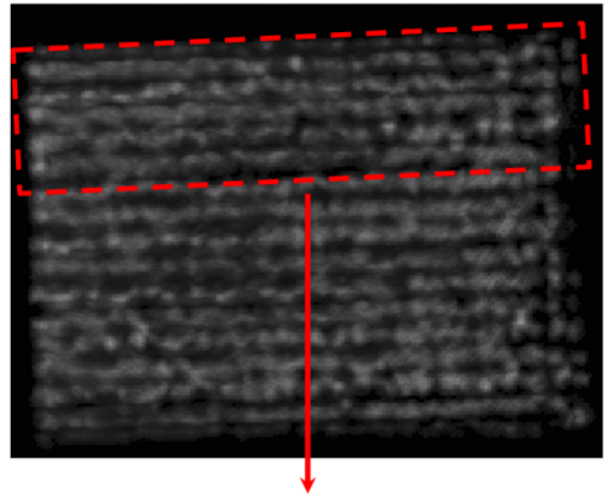
Ultrasonic scans of Electron Beam Free Form Fabrication (EBF3) AM block illustrating the variability of attenuation due to anisotropic grain structure.

5 MHz Immersion C-Scan

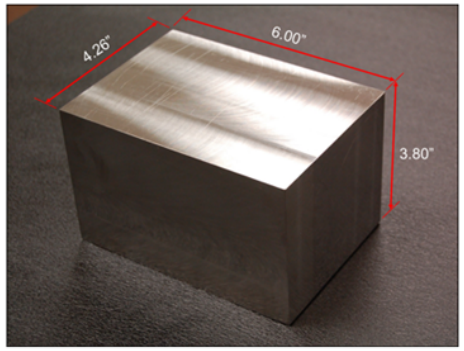




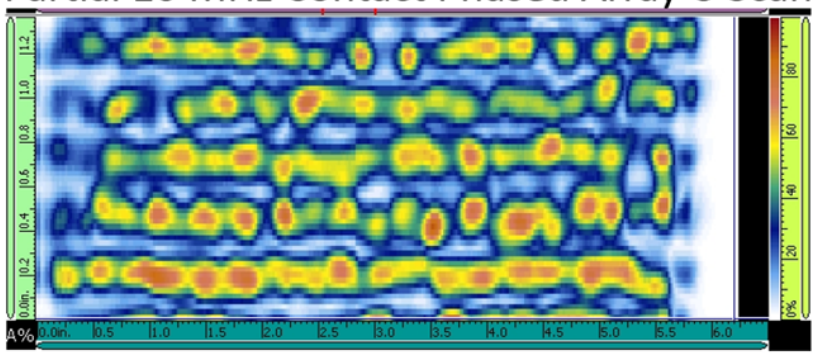
10 MHz Immersion C-Scan



EBF3 AM Block



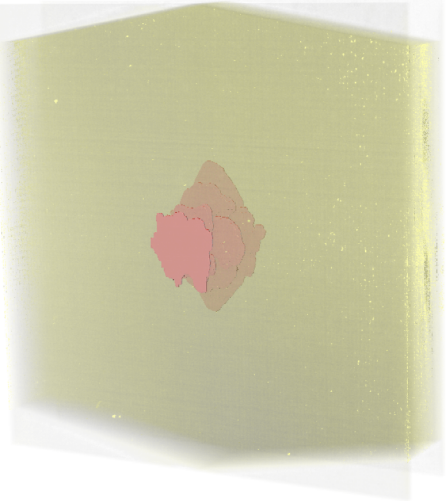
Partial 10 MHz Contact Phased Array C-Scan



Rapid Anomaly Detection for NDE of Composite Materials Highlights from Recent Research

Nondestructive Evaluation Sciences Branch

Collaborative Effort with Computational Digital Transformation Team

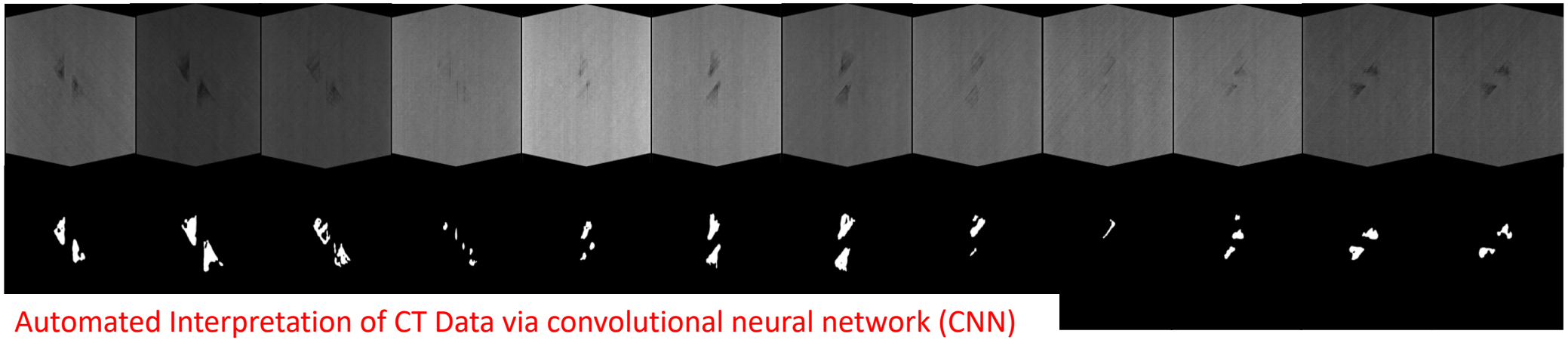


Goal: Develop algorithms to automatically rapidly detect, locate and size various kinds of anomalies saving SME time, and enabling discovery of anomalies, to help detect different failure modes for better design of material compositions and structures

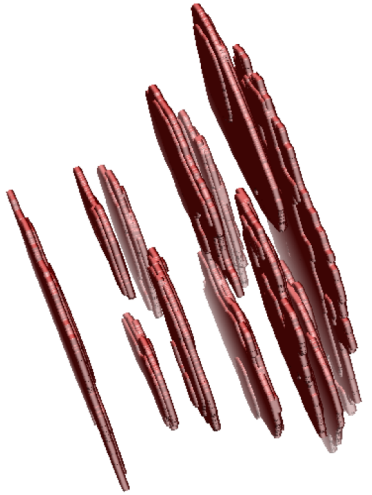
Application: CT results to be incorporated into structural analysis code for calculation of residual life/residual strength of composite

Outcome(FY16): Provide algorithms to NDE SMEs for graphite epoxy CT analysis saving time, discovering additional anomalies, and detecting failure modes.

FY17: Follow on project will be looking at using Monte Carlo based part simulation to test automated analysis techniques. This effort will attempt to establish methodology for qualifying automated analysis techniques. POC – Probability of Characterization

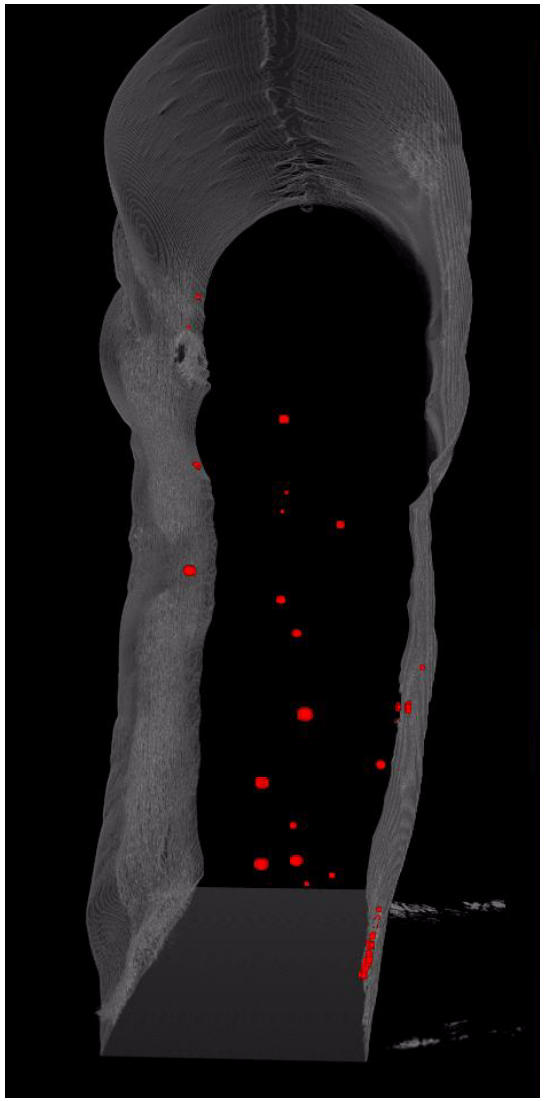


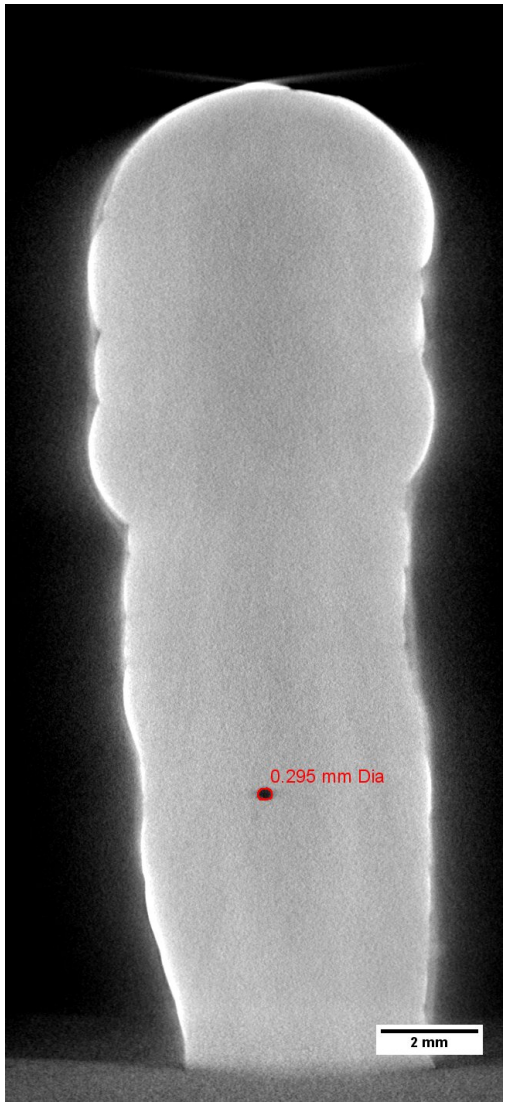
Automated Interpretation of CT Data via convolutional neural network (CNN)



Computed Tomography (CT) On AM Part

- X-ray slice data is generated using an X-ray source that rotates around the object; X-ray sensors are positioned on the opposite side of the circle from the X-ray source. Many data scans are progressively taken as the object is gradually passed through the gantry.
- Typical voxel Resolution will be between 12 & 15 microns depending on the size of the sample.
- High X-ray flux is required compared to composite materials. Samples at 125Kv produced high fidelity volumes with little beam hardening or artifacts.
- In addition a full volumetric scan allows for geometric dimensioning and tolerancing and void identification.





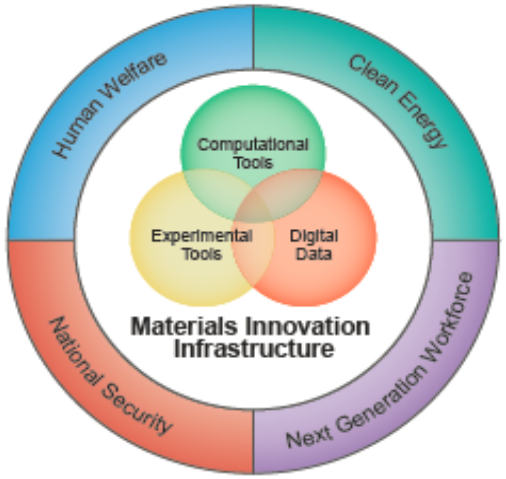




National Materials Genome Initiative (MGI)

- In June 2011 the National Materials Genome Initiative (MGI) was announced. MGI was established to be a *"multi-stakeholder effort to develop an infrastructure to accelerate advanced materials discovery and deployment in the United States. Over the last several decades there has been significant Federal investment in new experimental processes and techniques for designing advanced materials. This new focused initiative will better leverage existing Federal investments through the use of computational capabilities, data management, and an integrated approach to materials science and engineering."* [1]

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Materials Genome Initiative Overview [1]

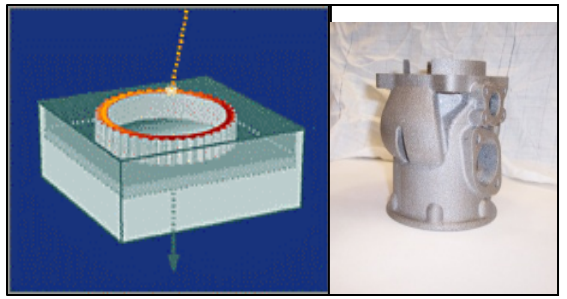
Materials Genome Initiative and Additive Manufacturing

Nondestructive Evaluation Sciences Branch

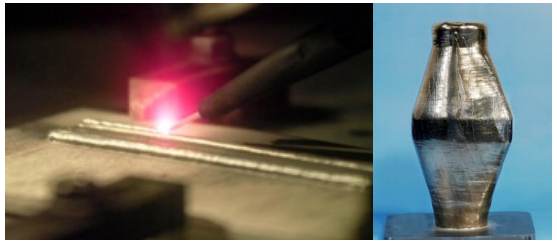
Description:
Additive manufacturing processes are being investigated for manufacturing of new and replacement parts.

Objective:
- Develop process parameter / microstructure relationships to reduce process optimization time.
- Develop thermodynamics relationships for process melt pool to understand microstructure and residual stress evolution.
- Develop microstructure / behavior relationships to guide design.
- Enhance SLM validation processes for SLS flight hardware.

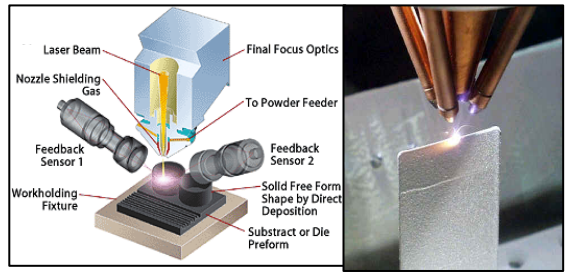
Why this technology:
- Computational modeling tools for metallic materials are relatively advanced (thermodynamic microstructural models, microstructural damage models).
- Commercial process modeling codes and research level process physics codes for additive manufacturing are available for evaluation.
- Large data set of process/microstructure exists from previous and existing NASA projects.
- Additive manufacturing has high degree of variability and ability to tailor microstructure, therefore computational materials approaches are necessary.



Laser Sintering/E-beam Melting



Electron Beam Freeform Fabrication



Laser Net Shaping

SLM Systems at MSFC

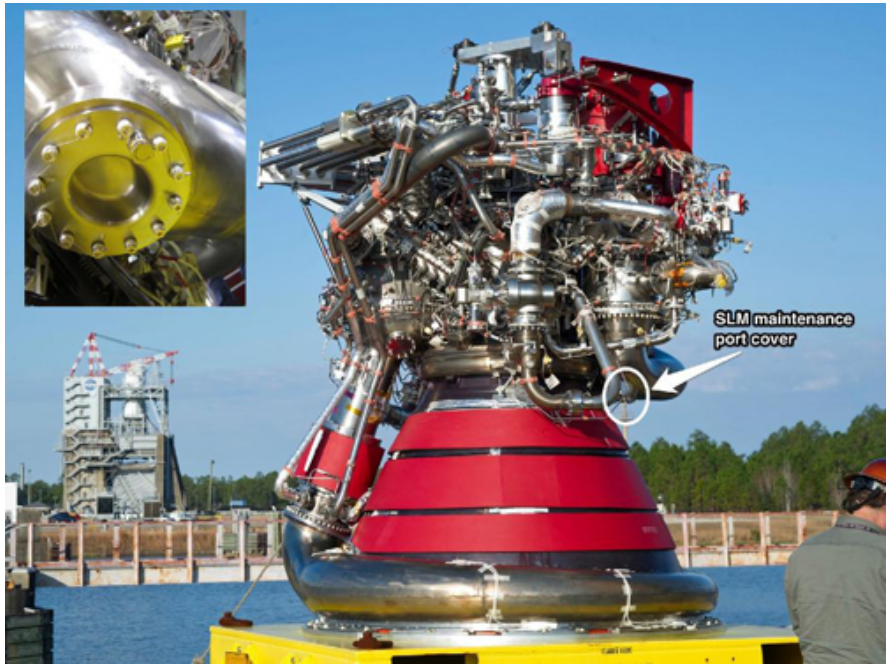


Concept Laser M2 Cushing System @ MSFC

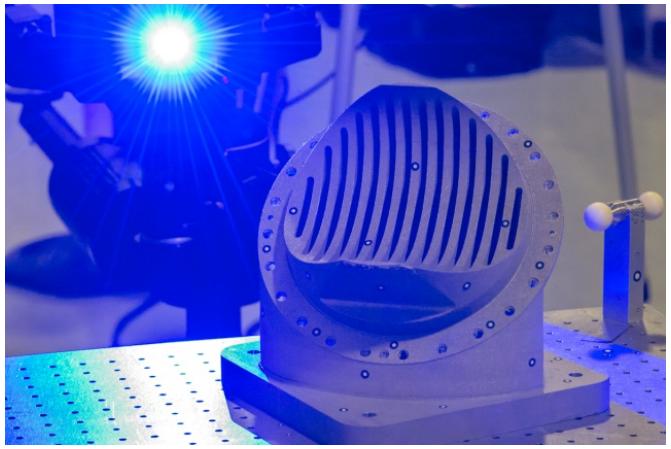


Concept Laser XLINE System @ MSFC

Additive Manufacturing in SLS



RS-25 Engine prior to testing
at Stennis Space Center



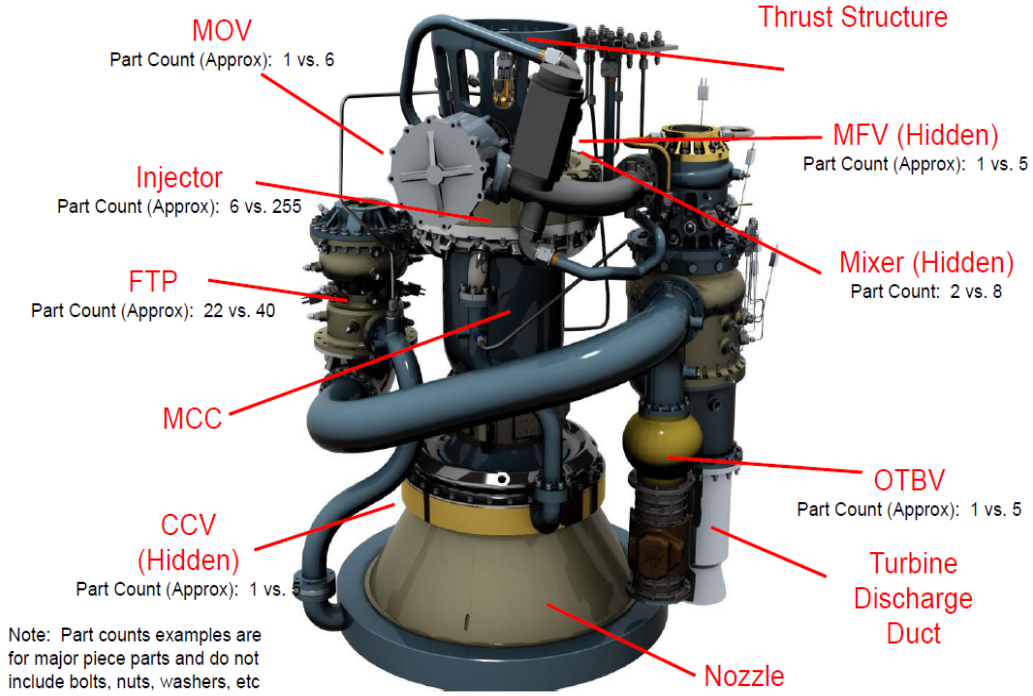
Pogo Z-Baffle made from
Selective Laser Melting (SLM)

What can MGI do for SLS

- Improve Process Certainty
  - Design / Tailor Process
- Improve Part Certainty
  - Meet material specifications
  - Certify components

Additive Manufacturing Benefit Example

AM will create reductions in Design, Development, Test and Evaluation (DDT&E), hardware lead time, cost and part counts can be dramatically reduced:



Reduction in parts count for a rocket engine

State of the Art for Typical Engine Developments	Prototype Additive Engine
• **DDT&E Time** – 7-10 years	• **DDT&E Time** – 2-4 years
• **Hardware Lead Times** – 3-6 Years	• **Hardware Lead Times** – 6 Months
• **Testing** – Late in the DDT&E cycle	• **Testing** – Testing occurs early in the DDT&E cycle
• **Engine Cost** – $20 - $50 Million	• **Prototype Cost** – $3-5 Million
• **Applicability** – Design for particular mission by a particular contractor – Often proprietary	• **Applicability** – Provide relevant data to multiple customers (SLS, Commercial partners, other government agencies) – Flexible test bed configuration can accommodate other's hardware / design concepts

https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20160004218.pdf

Thermal Modeling of Additive Manufacturing

Nondestructive Evaluation Sciences Branch

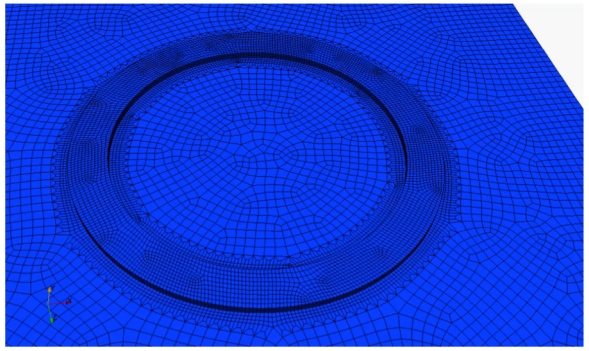
PROBLEM: The performance of additive manufactured parts relies on the thermal history throughout an entire component. This requires understanding of the thermal history of entire components for material from the molten state to room temperature.

Objective: Develop thermal models to predict material solidification and cooling as a part is manufactured. These models will be used to predict part distortion and residual stress and to guide the manufacturing process to reduce the time and cost to integrate additively manufactured components in service.

Approach: 3D FEM models incorporating transient heat diffusion with phase change (thermal model) and Eigen strains (distortion and residual stress models) were developed and compared to experimental observations.

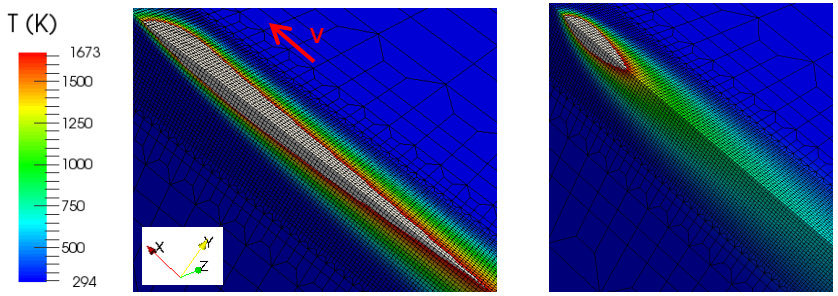
Impact: Thermal models applied to evaluate melt pools for use on old and new ("production") systems. The parameters necessary on new system to develop similar processes is very different. These modified parameters have been supplied to MSFC.

Thermal model of SLM build
(powder bed not shown)



Thermal model of melt pool for adjusted scan speeds on old (M2) and new (XLINE) SLM systems

XLINE: v=2500 mm/sec M2: v=600 mm/sec



White shows melted region ($T>T_{melt}$)

Thermal Modeling of Additive Manufacturing Process Parameters

PROBLEM: Selective laser manufacturing is a complex process, with many variables associated with the machine, processing parameters, initial material, and build geometry. To develop a certifiable process, accurate information must be stored and evaluated critically.

Objective: Develop a data schema for a complex data management system that can be used to track the process configuration and identify uncertainties and potential issues in the process.

Approach: NASA worked closely with the Materials Data Management Consortium to develop the data schema for an existing materials data management system specific for additive manufacturing.

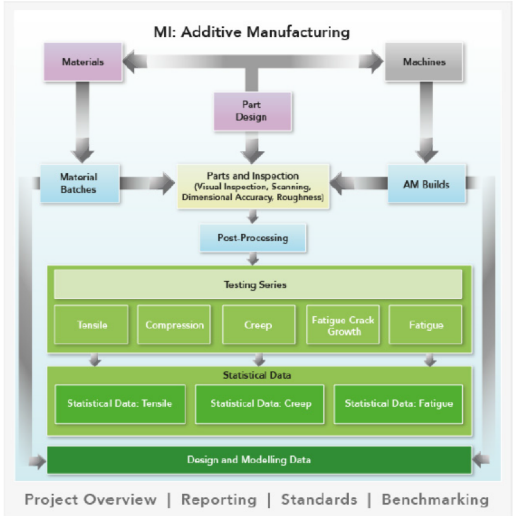
Results: The proposed schema will be shared with the manufacturing team and MSFC and the MI Granta software will also be supplied.

Inputs for an AM data schema

Machines	Materials	Part Design
General Information	General Information	General Information
Calibration	General Properties	Original Design
Machine Specifications	Composition overview	Re-Design
Material	Bulk Mechanical Properties	Dimensions
Machine Properties	Bulk Thermal Properties	General Material Properties
Build Environment	Bulk Electrical Properties	Processing
Laser Properties	Biological	Static Tensile Properties
Electron Beam Properties	Chemical	High-cycle fatigue properties
	Eco	Fracture Toughness
	Cost	Fatigue Crack Growth
	Safety and Handling	Surface Roughness Requested
	General Information	Other Requested Properties
	Requirements	Final Part Details
	Composition	Quality Assurance
	Physical Properties	Key Benefits
	Further Information	

Material Batches	Builds	Parts
Project Information	Project Information	Project Information
General Batch Information	General Information	Part Information
Manufacturing	Build Information	Part Specifications
Material Quality	General Build Parameters	Samples
Particle Properties and Size Distribution	Build Atmosphere	Visual Inspection
Interstitial contamination	Material Used	Accuracy Testing
Flowability	Support	NDT Testing
Wire Properties	Filament Information	Post Processing
Chemical Analysis and Composition	Substrate	Heat Treatment
	Quality of Welding Consumables	HIP
	Build Alarms	Machining
	Themes Used	Laser Polishing
	Powder Build Parameters	Other Post Processing
	Wire Build Parameters	
	Laser Properties	
	Electron Beam Properties	
	Arc Properties	
	In-Process Rolling	
	In-Process Analysis	

Flow for an AM data management system



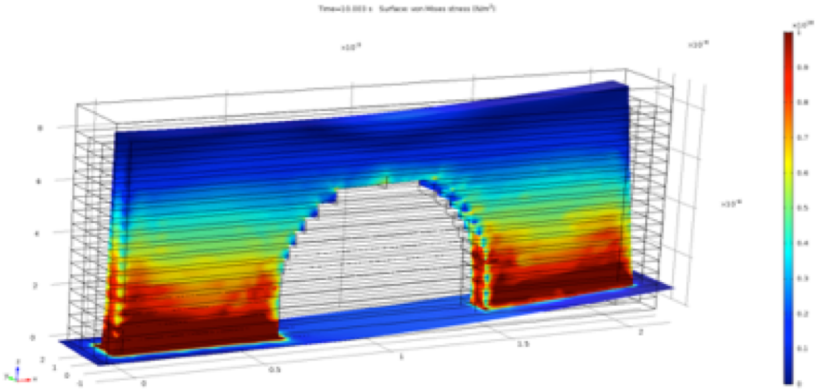
3D Deformation Behavior for SLS parts

Objective:

Predict 3D part distortion for pogo z-baffle test article using thermal contraction and residual stress models.

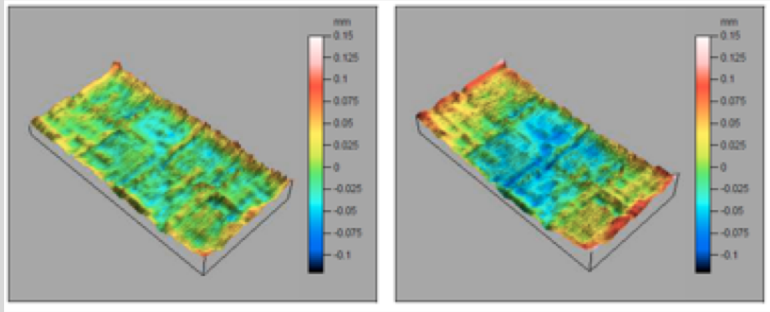
Key Accomplishment/ Deliverable/Milestone:

- Demonstrated 3-D model in COMSOL for modeling part distortion and stresses in selective laser melting additive part manufacturing resulting from given process parameters.
- Analyzed thin wall arched part of IN718 used as a benchmark to bound worst-case distortions.
- Identified automation necessary for part scale-up.



Significance:

- Proved that COMSOL is capable of modeling part distortions from layer by layer additive manufacturing.
- Distortions predicted can be improved by calibrating laser power in simulation via experiments with power through machine optics.
- Not all material parameters for IN718 needed are currently available, phase change not represented due to scale of whole part.



Part on Build Plate Part Removed from Build Plate

Graphs showing Distortion

Process Control Tool (in-situ monitoring system) to SLS Program

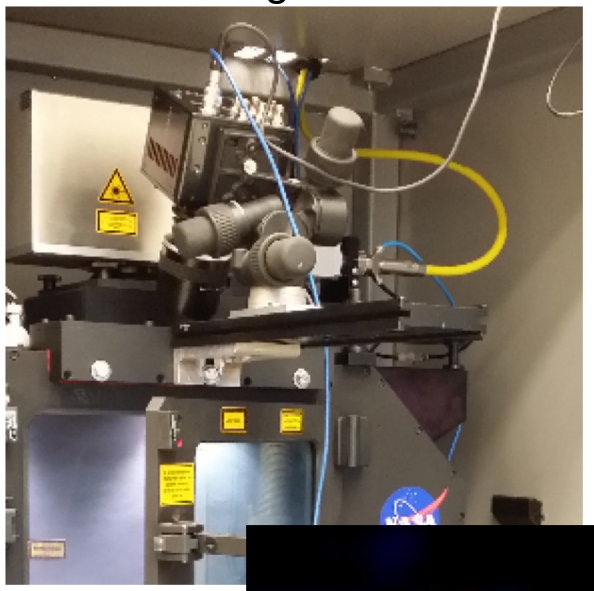
Nondestructive Evaluation Sciences Branch

Objective:

Provide a methodology to the SLS program for optimizing process development for additive manufacturing of a component. Demonstrate how this methodology could be applied to an additively manufactured component to reduce process development time. Demonstrate how this methodology can be applied to other components suited for additive manufacturing.

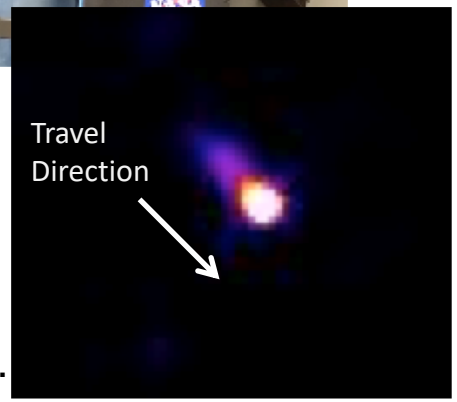
Key Accomplishment

- A process control tool (using in-situ monitoring to link thermal models to actual production) has been developed and successfully demonstrated on LaRC Electron Beam Freeform Fabrication (EBF3) system and is being successfully used to reduce manufacture time.
- Candidate camera and optics combinations were investigated on the MSFC M1 machine to evaluate their ability to image the much smaller melt pool produced during SLM.
- Both Near-Infrared and Mid-Wave Infrared sensors were successfully used to image the melt pool in real time. Data collected shows potential to monitor build metrics: melt pool/tail area size and shape in addition to build temperature for closed loop control.



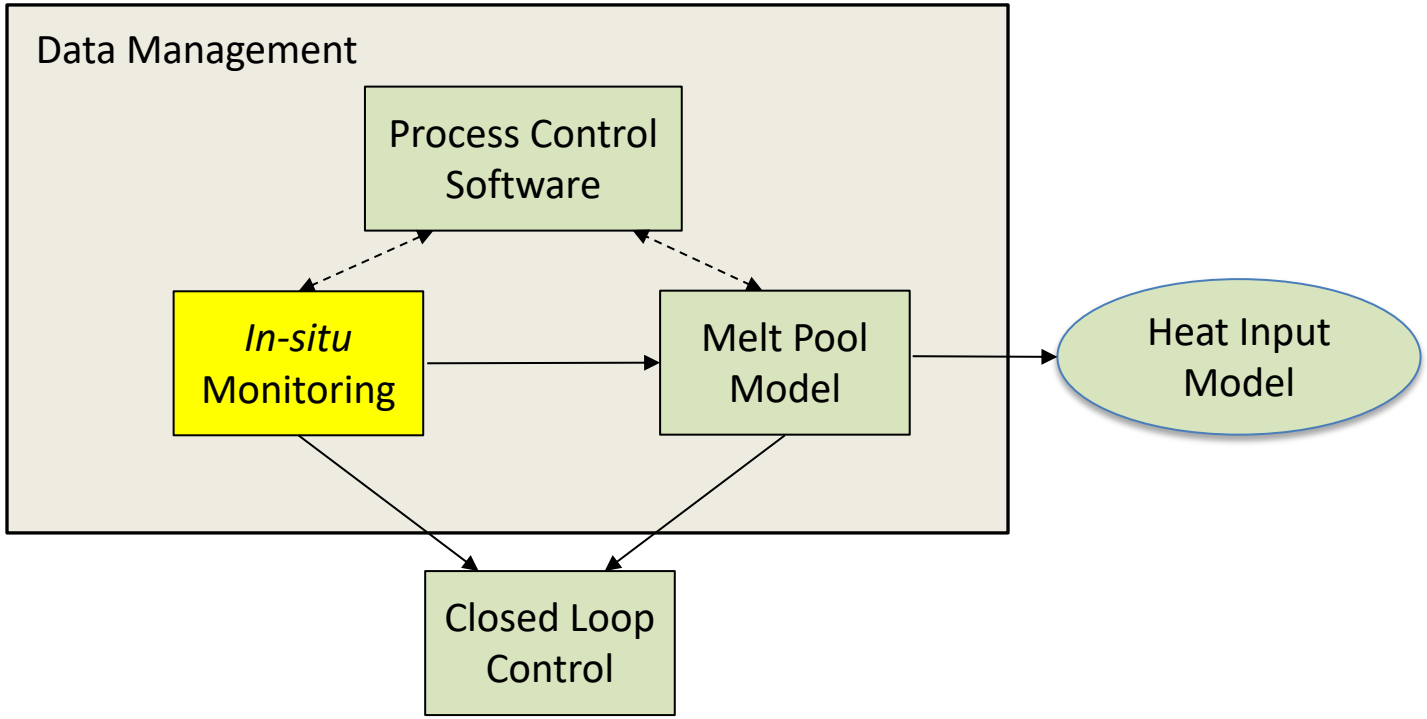
Significance:

- Thermal models of the melt pool were demonstrated to reduce the process parameters development by over 80% in one test case. In-situ monitoring of the melt pool is necessary to realize this benefit in other components in order to link thermal model outputs to actual production.
- To extend the previously developed in-situ monitoring and control tool from EBF3 to the smaller SLM machine and melt pool, potential camera and optics systems were investigated and successfully demonstrated.



Near Infrared Image of the melt pool and semi-solid tail areas.

In-Situ Monitoring Development for Additive Manufacturing

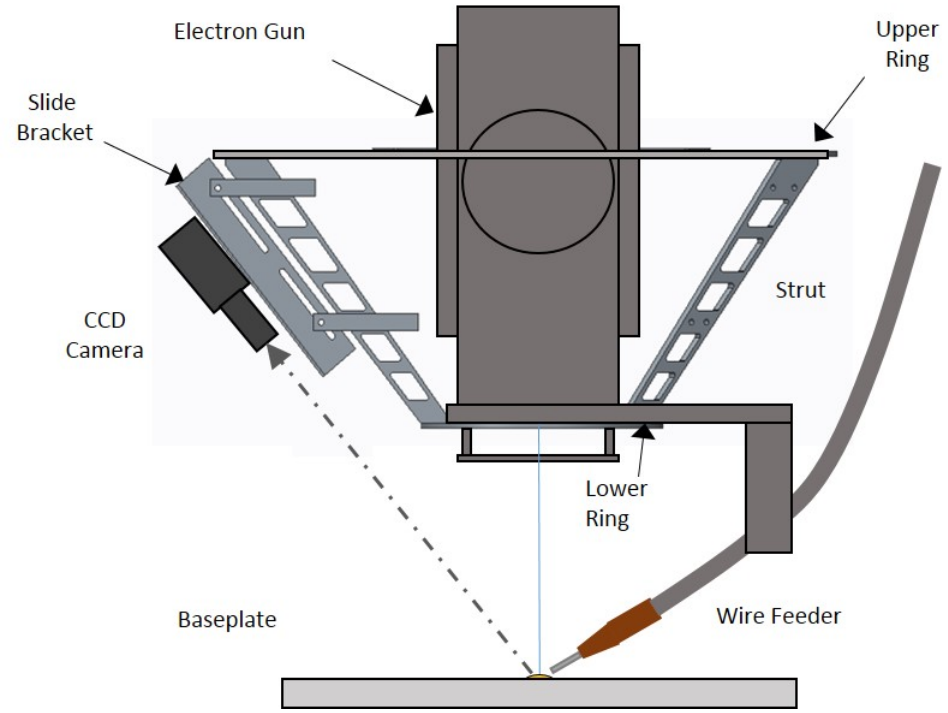


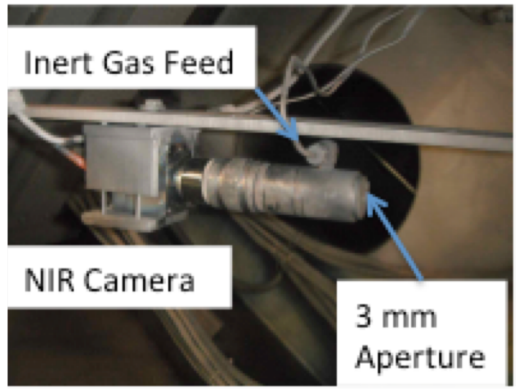
Objective: Develop and demonstrate in-situ monitoring techniques for additive manufacturing processing.

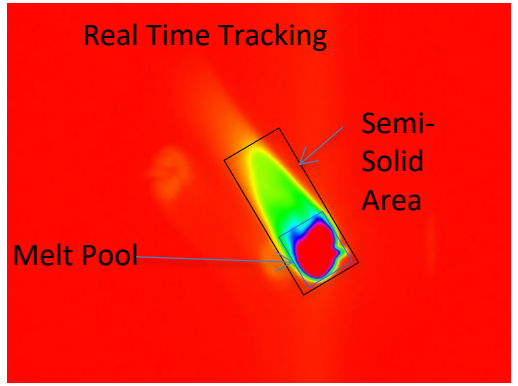
Significance: In-situ monitoring is necessary to provide metrics (melt pool area and semi-solid regions) for closed loop control, real time nondestructive evaluation, and record temperature anomalies.

In-Situ Monitoring of EBF3 Additive Manufacturing

Nondestructive Evaluation Sciences Branch





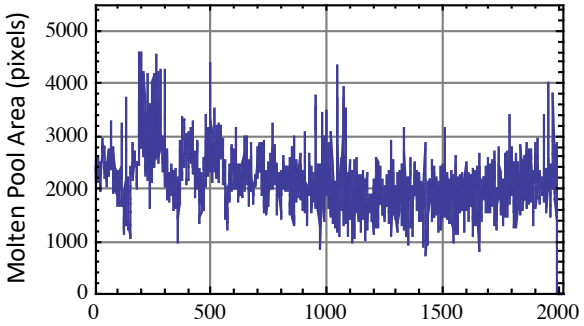


Approach

Acquire calibrated temperature images and apply advanced image processing techniques to determine deposition metrics: molten pool size and semi-solid area in real time for closed loop control.

Technical Challenges

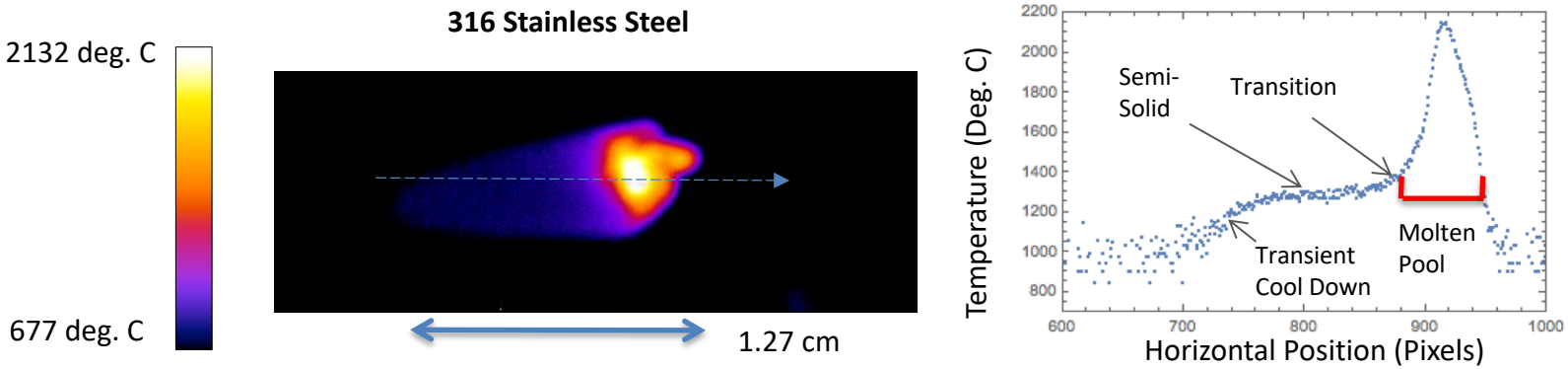
Emissivity variation as a function of temperature and wide range of wire metal melting temperatures require different imaging wavebands.



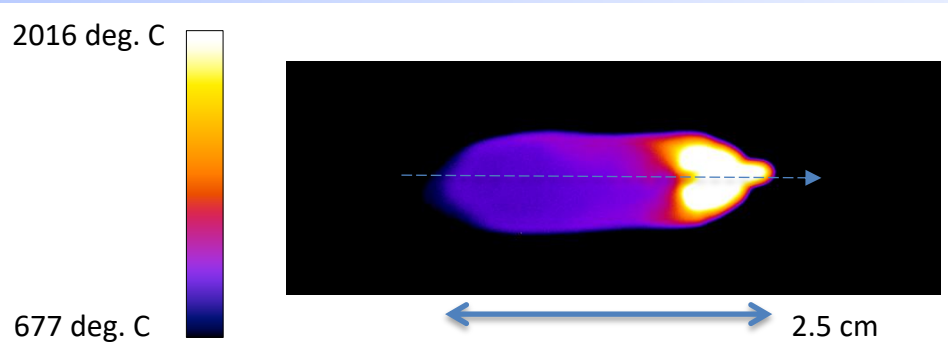
In-Situ Monitoring of EBF3 Additive Manufacturing of Various Metals

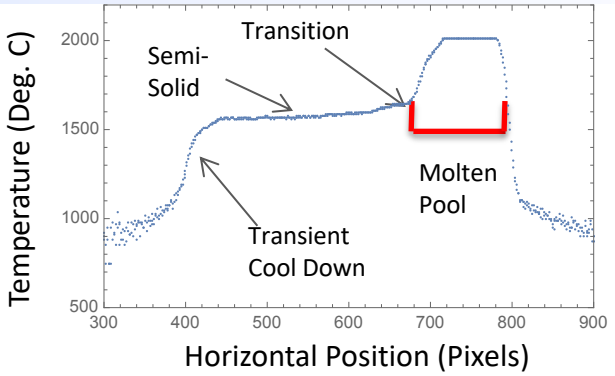
A radiometric calibration was used to convert the pixel values (intensity counts) to approximate temperature.

- Define the temperature imaging limits of the sensor.
- Selection of optimal sensor integration time for a given metal.
- Determine the optimal threshold values for closed loop control metrics based on the wire melting temperature.
- Unknown emissivity at molten pool area results in large temperature measurement errors.

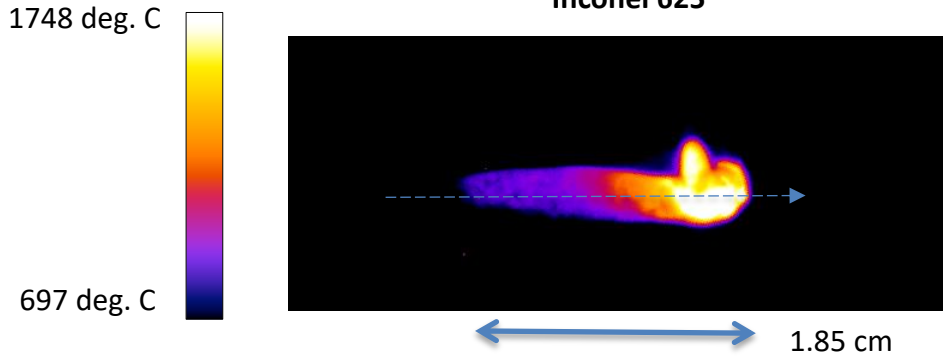


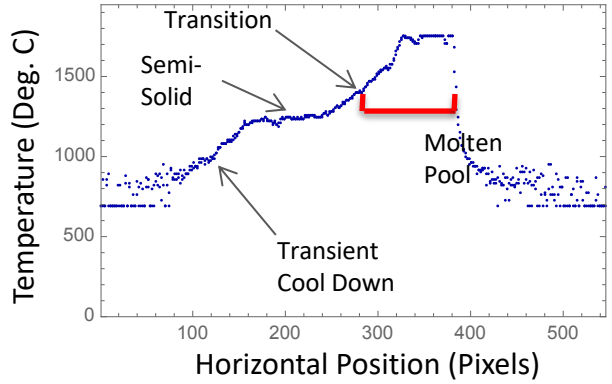
In-Situ Monitoring of EBF3 Additive Manufacturing of Various Metals



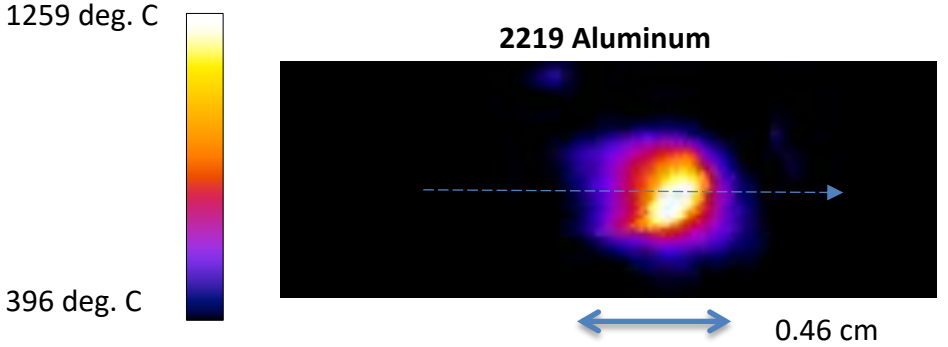


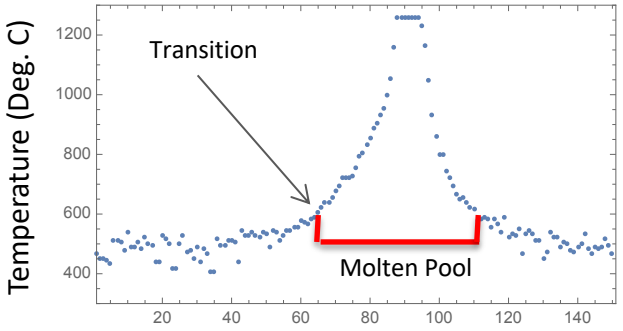
Inconel 625



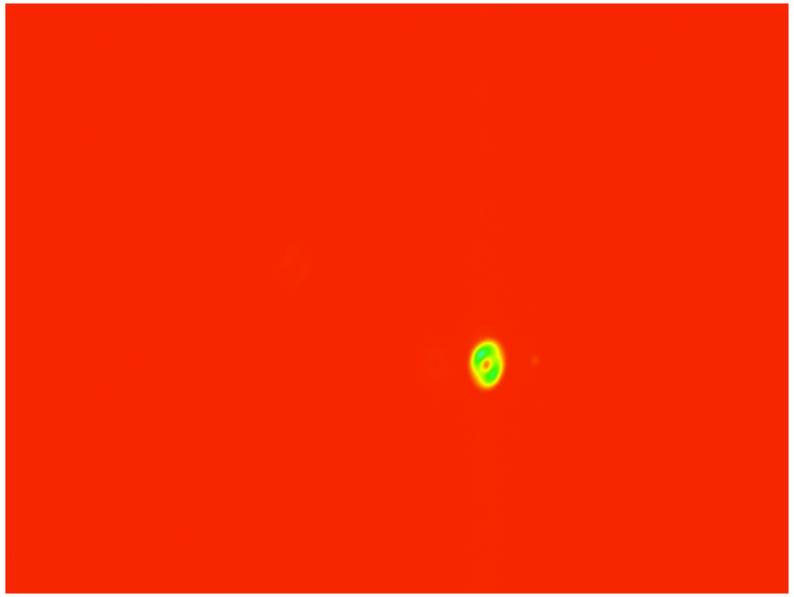


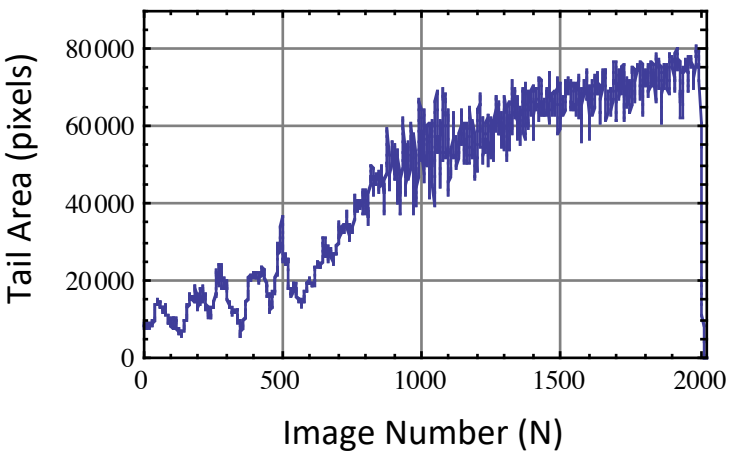
2219 Aluminum

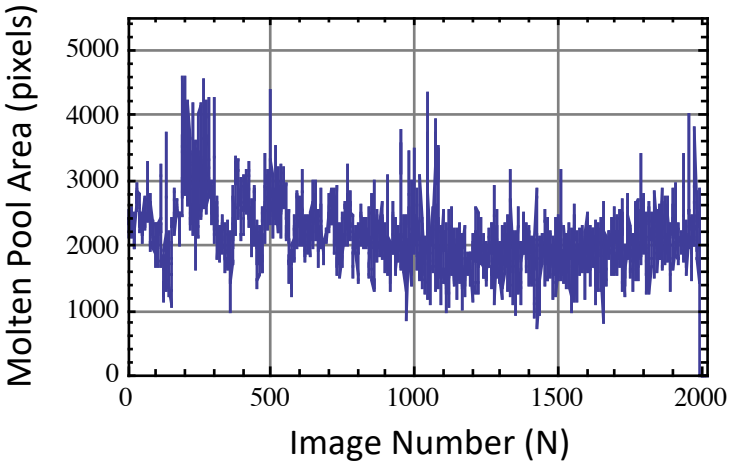




In-Situ Monitoring of EBF3 Additive Manufacturing

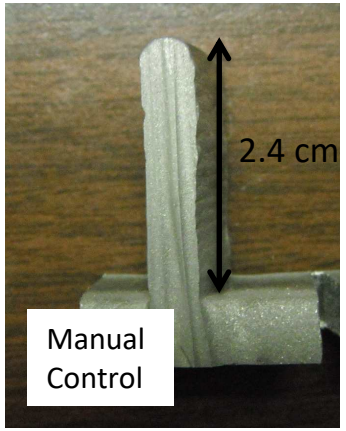






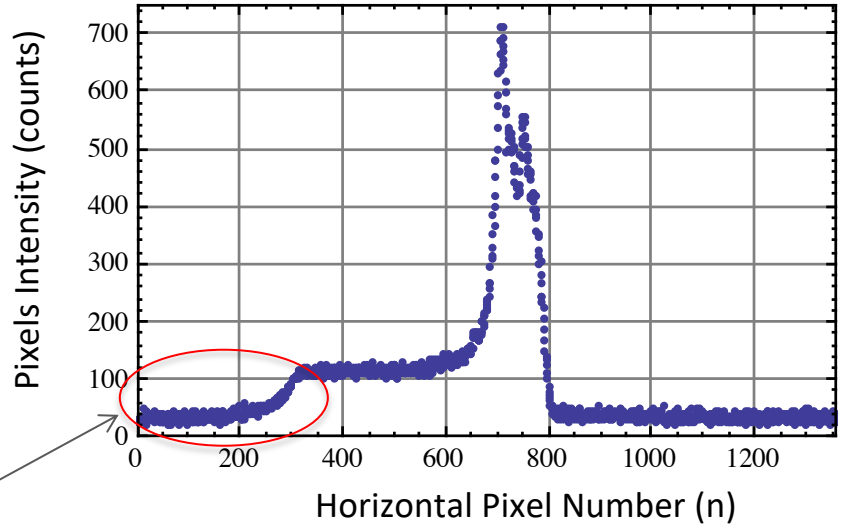
In-Situ Monitoring of EBF3 Additive Manufacturing: Closed Loop Control







In-Situ Monitoring of EBF3 Additive Manufacturing: NDE

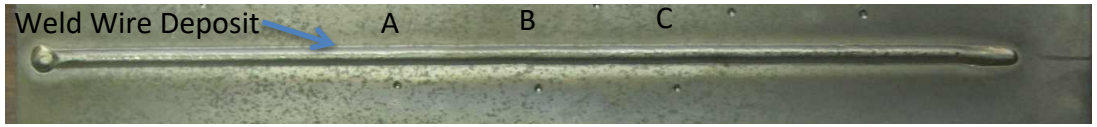


Transient
Cool Down

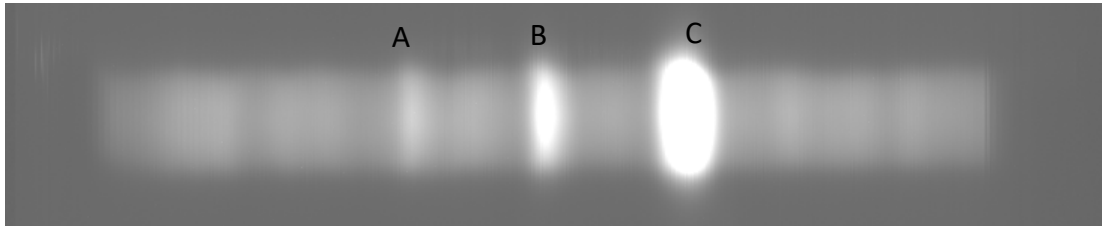


Back View

27.3 cm



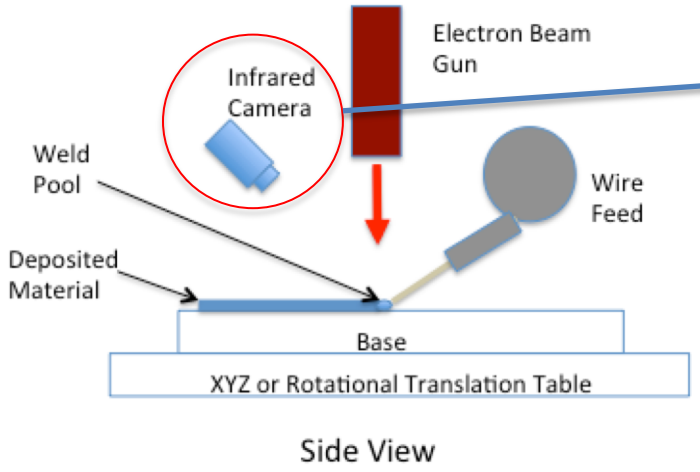
Front View



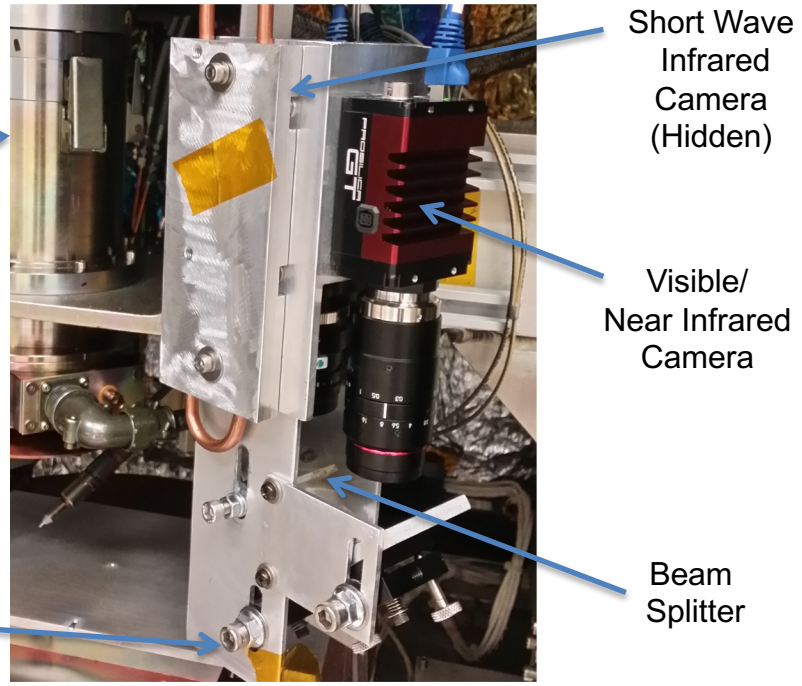
NDE Image

In-Situ Monitoring of EBF3 Additive Manufacturing (Dual Band Imaging)

Electron Beam Fabrication System



Dual Band Imaging System

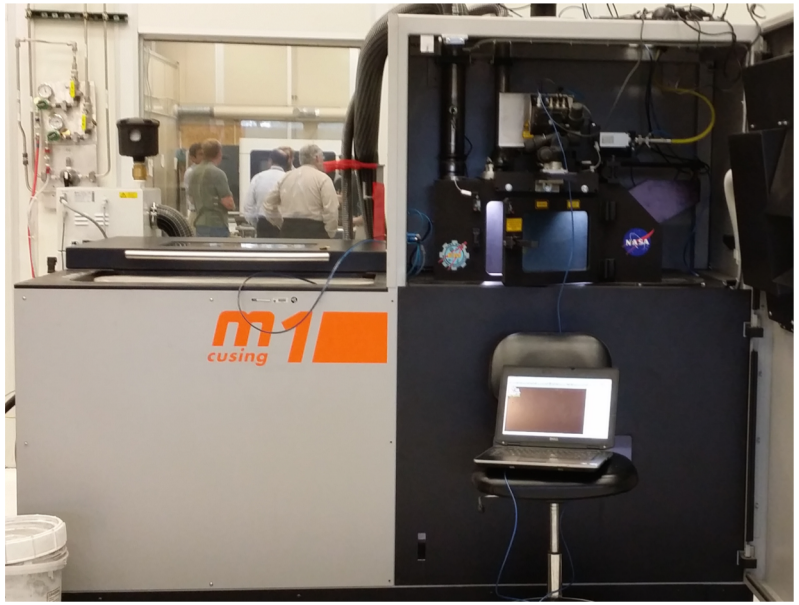


Objective: Melt pool imaging requires higher temperature measurements (NIR wavelength sensor), wire position requires visible sensor or the transient temperature cool down requires lower temperature measurements (longer wavelength sensors).

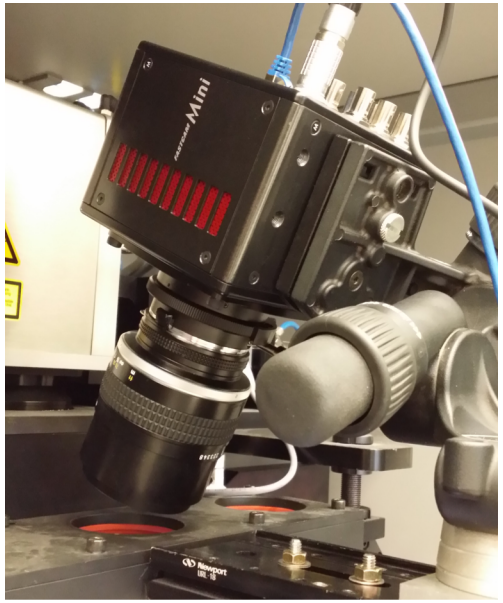
PROGRESS: To address this challenge a dual band imaging system was recently developed using a beam splitter to image various wavebands for improved in-situ monitoring, LaRC Patent Disclosure LAR18445-1.

SLM In-Situ Monitoring Development

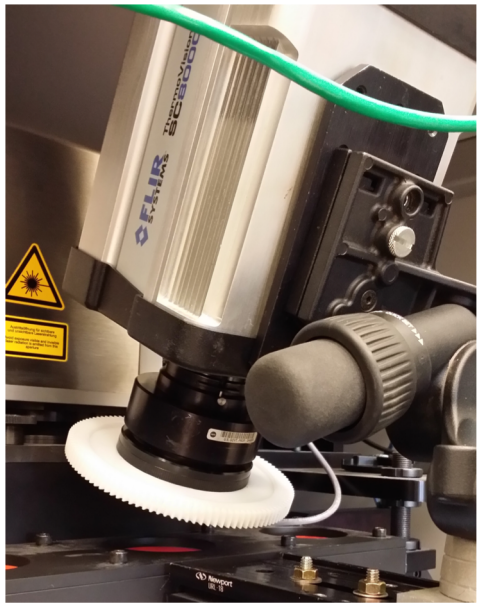
M1 Concept Laser Fabrication System



High Speed NIR



High Speed MWIR



- Near infrared camera: 10,000 frame per second, 1024 x 672 pixel array size, 12 bits dynamic range, 200 mm zoom lens, and resolution of approximately 37 microns/pixel.

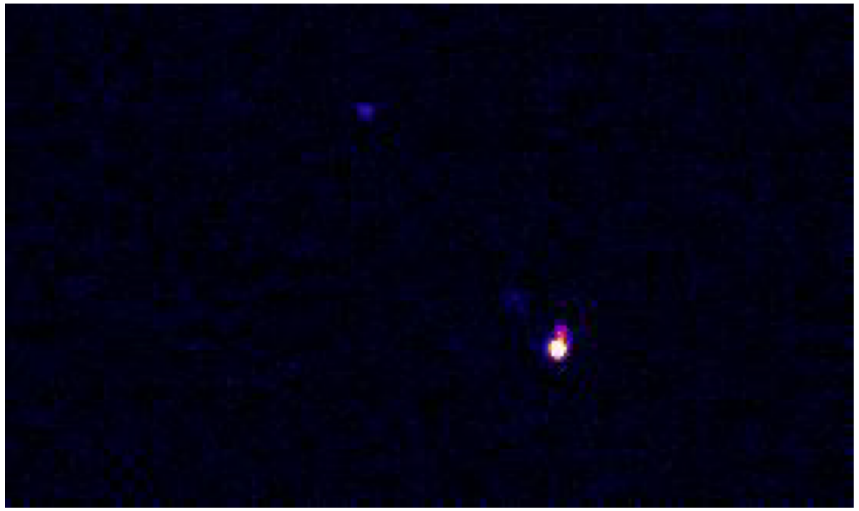
- MWIR camera: 3,100 frame per second, 128 x 16 pixel array size, 14 bits dynamic range, 100 mm zoom lens, and resolution of approximately 62 microns/pixel.

SLM In-Situ Monitoring Development

M1 Concept Laser Fabrication System



High Speed NIR

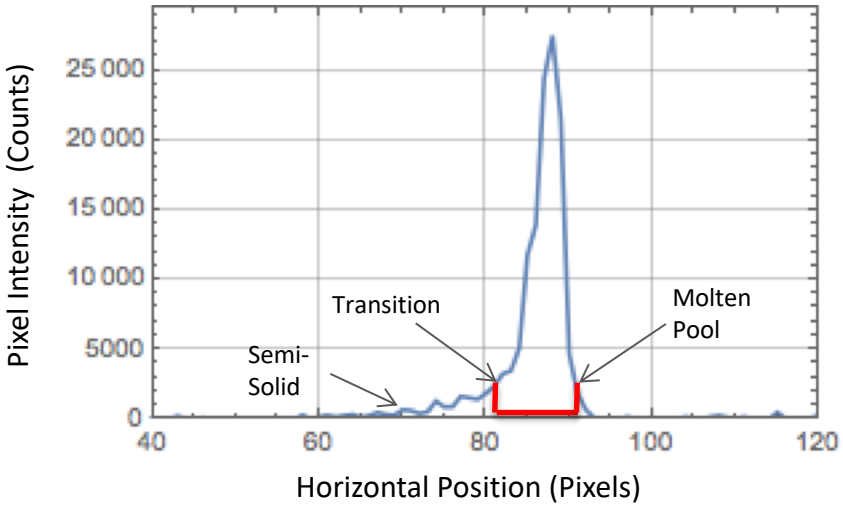


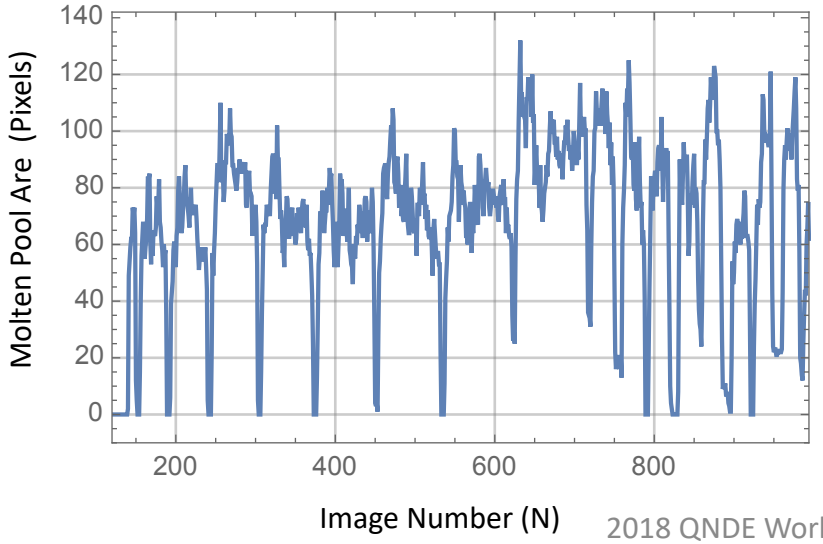
High Speed MWIR



SLM In-Situ Monitoring Development







Challenges: Improve resolution (optical path on axis to laser), faster processing required for closed loop control, real time tracking, and dual band sensor for detection of melt pool and transient responses.

SLM In-Situ Monitoring Development

- *Summary of Accomplishments*
  - Developed dual band imaging system for in-situ NDE, LaRC Disclosure LAR18445-1
  - Evaluated IR camera systems, compatible with existing M1 system at MSFC.
  - Demonstrated of preliminary process monitoring capability consisting of thermal measurements from IR camera EBF3 and SLM systems.
- *Recommendations for SLM Closed Loop Control*
  - Open ended custom system for access to laser power supply, optimize optical path/components and implement NIR sensors (similar to EBF3).
  - Radiometric and spatial calibration for quantitative build metrics (melt pool area, shape, semi-solid region, etc.)
  - High magnification on axis optical path (laser following) for thermal sensor system.
  - Real time particle tracking to reduce build metric errors.
  - Methodology for efficient data storage (compression algorithms) and viewing of the data.
  - Real time nondestructive evaluation using transient thermal response may require dual band imaging (longer wavelength sensing).
  - Location tracking for position identification on build part for post build inspection/certification.

Additive Manufacturing Structural Integrity Initiative

Overview:

- Overall project is a four-center (MSFC, LaRC, GRC, ARC) effort; MSFC is the overall lead
- Generating the foundational information needed to qualify the SLM process for human-rated spaceflight
- Validating the qualification methodology presented in the MSFC draft, *Engineering and Quality Standard for Additively Manufactured Spaceflight Hardware*
- Part defect assessment methodologies will be coordinated with NASA's NDE Working Group (OSMA)
- Primary focus is on Selective Laser Melting (SLM – a laser/metal powder bed additive manufacturing process) using Inconel 718

Overall Project Goal:

Generate fundamental understanding of the SLM process and Inconel 718 material characteristics resulting from the SLM process to support confidence and certification of components for use in SLS vehicles

SLM In-Situ Monitoring Development AMSII

Open Ended SLM System:

1) Imaging Fourier transform spectrometer (IFTS)
2) Phantom high speed camera
3) FLIR thermal camera
4) Near-Vis hyperspectral camera
5) Visible spectrometer

