ICME & Process Monitoring for Qualification of Nuclear Components via LPB-AM

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North Bethesda, MD

Parts of Presentation previously made at:

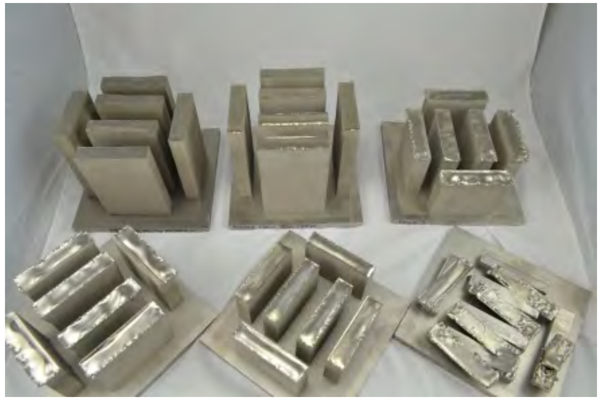
- US DOE Advanced Manufacturing Methods Workshop in Idaho Falls, October 2017
- And at ASME BPVC on Additive Manufacturing, November 2017

AMM
Advanced Methods for Manufacturing

Presentation Outline

- Introduction to DOE Project on AM
- Interest by Nuclear Industry and Applications
- Project Tasks & Progress
- What We Have Learned…
- Summary

Introduction—DOE Project



- ASME, NRC, and industry continue to look to identify strategy/approach for “nuclear quality components” manufactured by AM.
- Current approach requires manufacture of multiple parts followed by destructive testing of several parts
  - Properties (microstructural/mechanical) are still difficult to predict
- Objective: ORNL/EPRI are working on an approach that incorporates *Integrated Computational Materials Engineering (ICME)* and *In-situ Process Control* aimed at demonstrating **properties reproducibility** for nuclear applications using LPB-AM.

There has to be a better way to qualify AM parts for nuclear applications…..

Why Is Industry Interested in Laser Powder Bed-AM?

1. Produce replacement parts for the **existing fleet** with a very short turn around
   - Obsolete parts—remember some units are over 40 years old
2. Produce new or complex parts for the **new fleet** of ALWRs, SMRs and Gen IV applications
3. Design to include improved flow characteristics or special features that can't be done through casting/forging/ machining
4. Introduce favorable properties via unique microstructures
5. Design for performance

Chamber size: 250mm x 250mm x 300mm (~10x10x12)
(courtesy of Renishaw)

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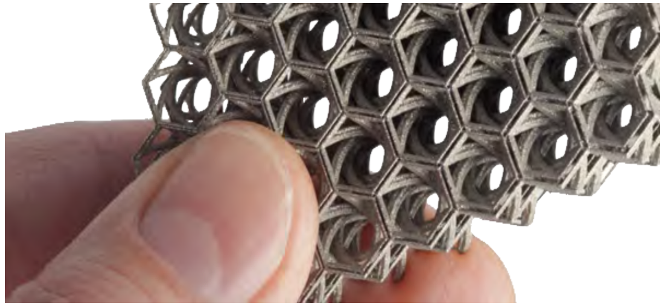
Examples: Nuclear Applications for AM
--Reactor Internals and Fuel Assemblies



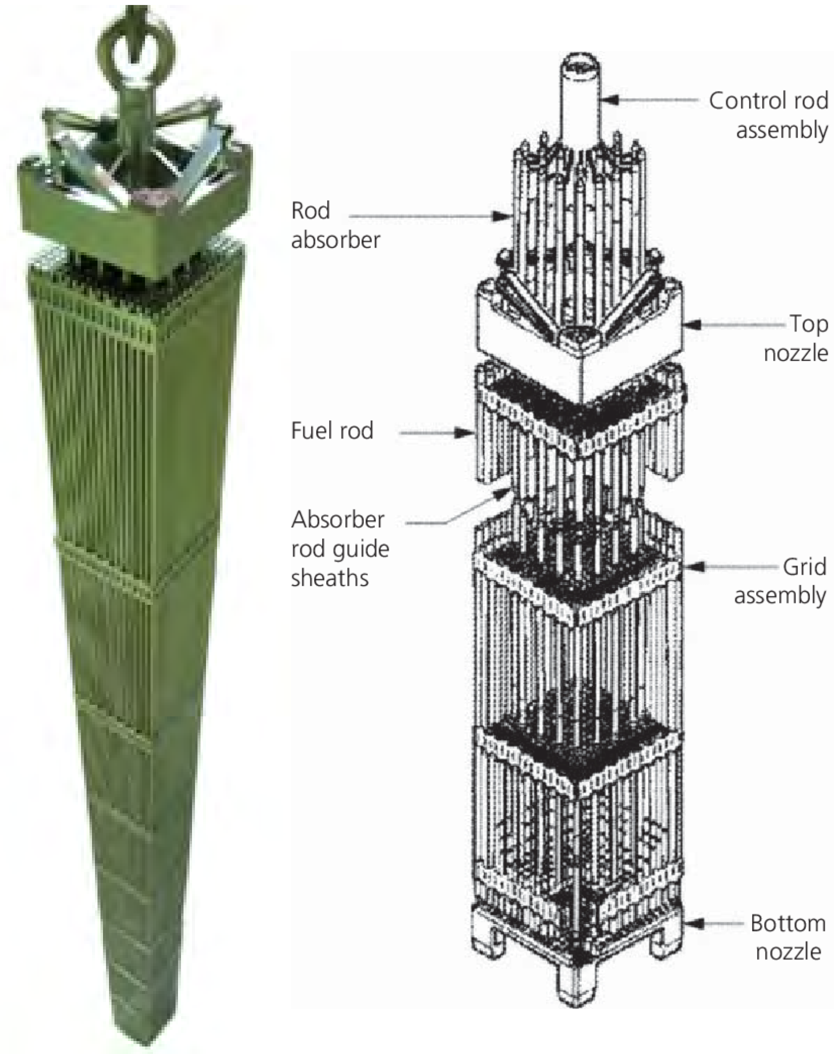
- **Smaller parts (<100 lbs, 45kgs)**

Potential Reactor Internals

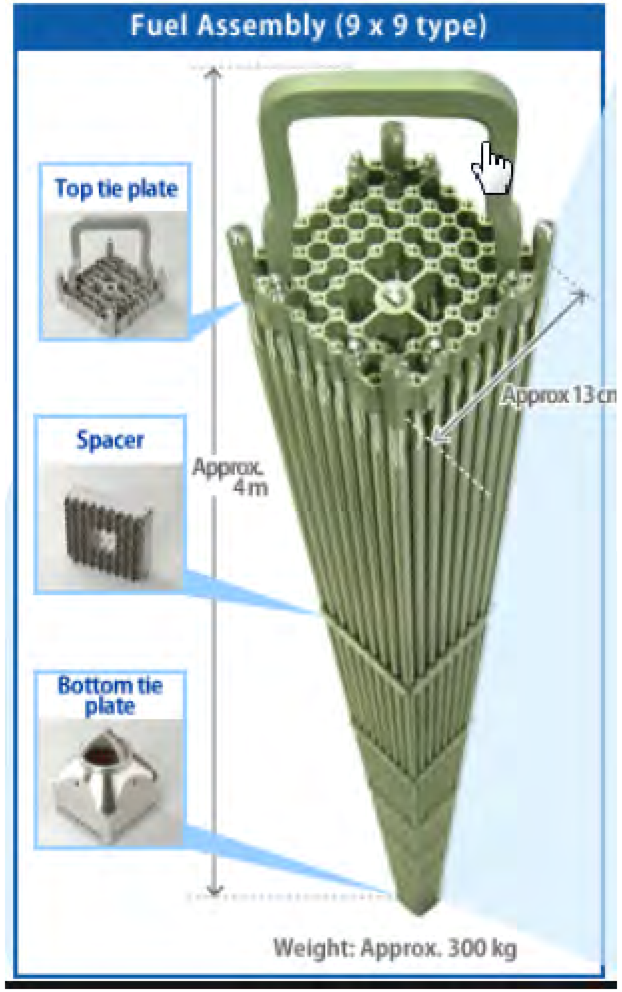
- Small valves, tees, wyes
- Fuel assemblies (next slide)
- Control rod drive internals
- Alignment pins & springs
- Small spray nozzles
- Instrumentation brackets
- Stub-tube/housing
- Steam separator inlet swirler
- Flow deflectors
- GEN IV—cooling channels

PWR Control Rod Assembly

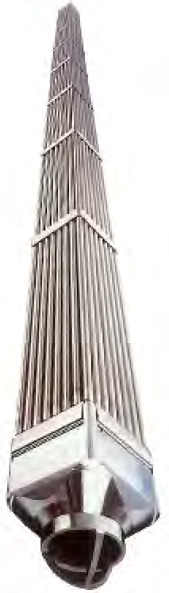
Fuel Assemblies--Examples

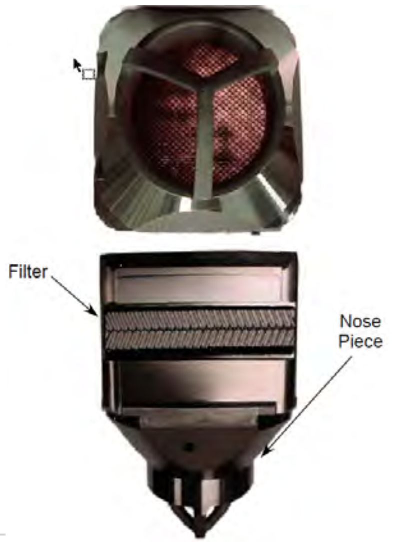


Courtesy of WEC



Courtesy of Hitachi





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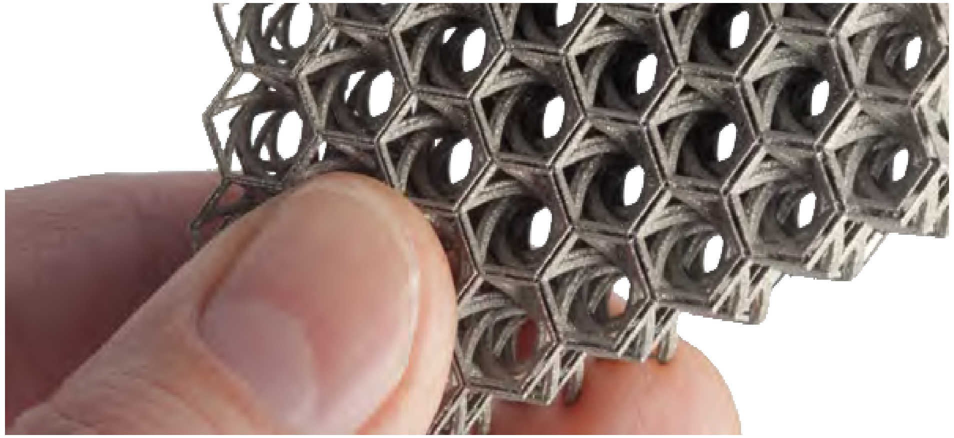
Current AM Limitations--Metallics

<u>6 Key Limitations</u>

- Chamber size
- Deposition rates, single laser or EB
- Porosity or lack of fusion
- Residual stresses/distortion
- Post processing required, HIP
- Layer-by-layer qualification (nuclear)



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Project Tasks

1. Demonstrate Artifact Design and Baseline Properties
2. Process Design, Processing and In-situ Monitoring & Validation
3. Deploy and Validate High Performance Computational Models
4. Ex-situ Non Destructive Microstructure Characterization
5. Scale up to Full Size Components
6. Develop ASME and Regulatory Acceptance

Task 1: Demo Artifact Design and Baseline Properties

- Produce two demonstration components (simple and complex).
- Measure/document static (yield strength, tensile strength, elongation) and dynamic (Charpy toughness & fatigue) properties.
- WEC and RR provide components/data for existing technologies (forging, casting, etc.) for comparison.

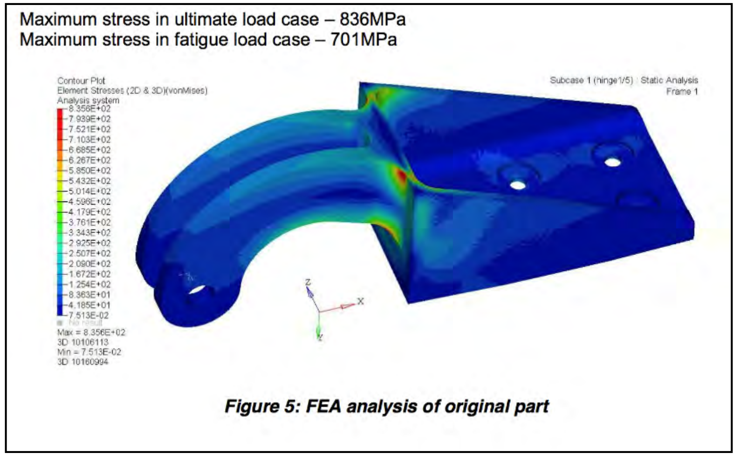
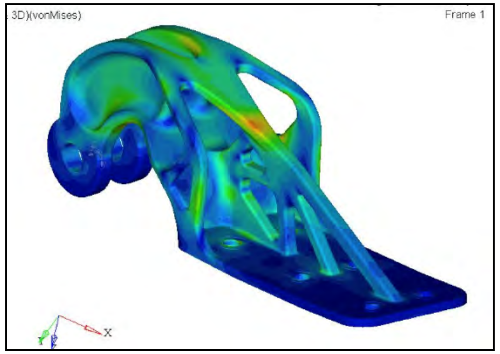


Figure 5: FEA analysis of original part



Application of Topology, Sizing and Shape Optimization Methods to Optimal Design of Aircraft Components

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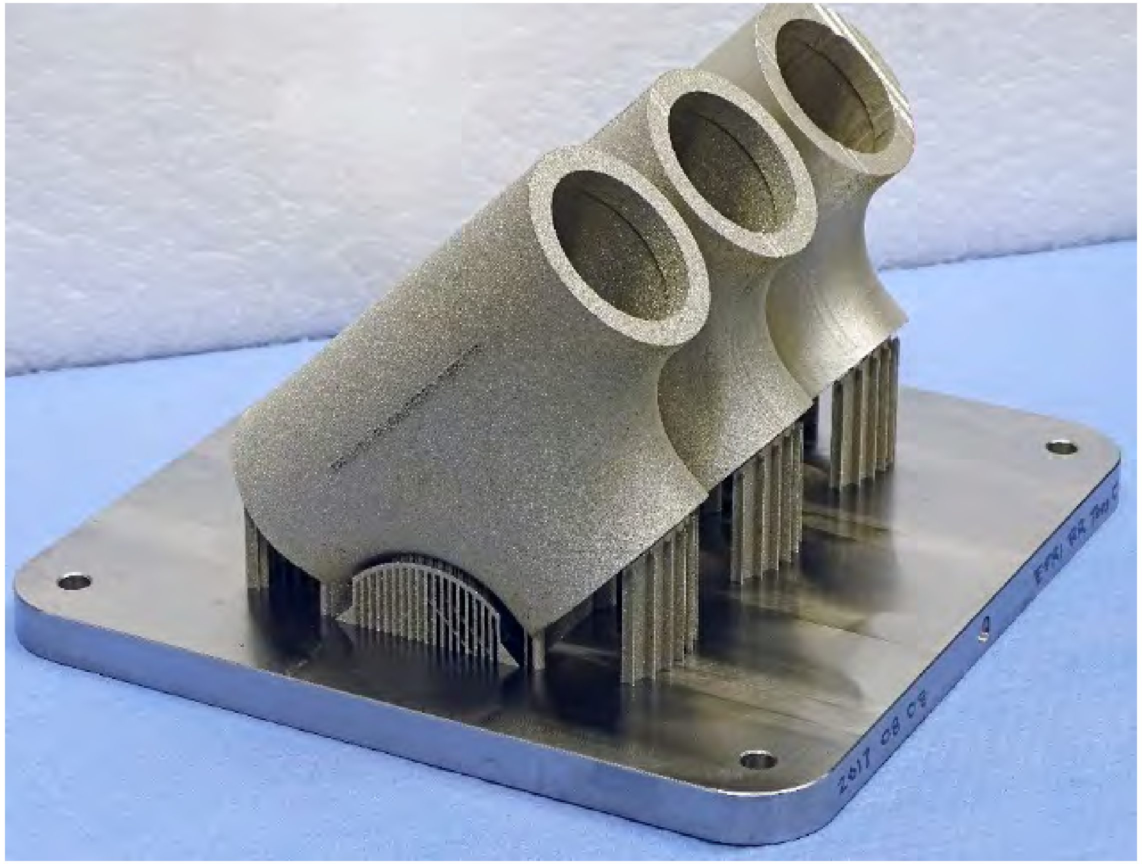
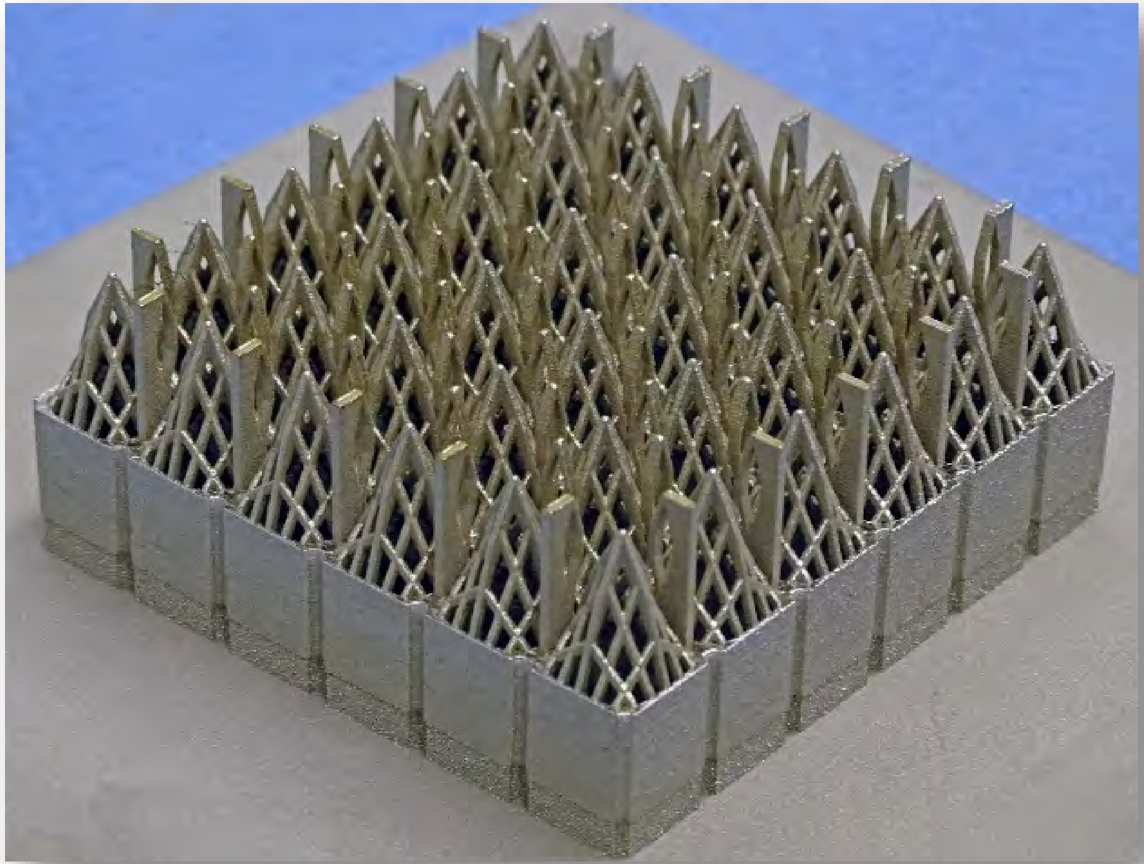
Additive Manufacturing (AM) of Reactor Internals



Rolls-Royce 2” diameter 316L SS Pipe
Tee-Sections, Build Time ~67 hrs

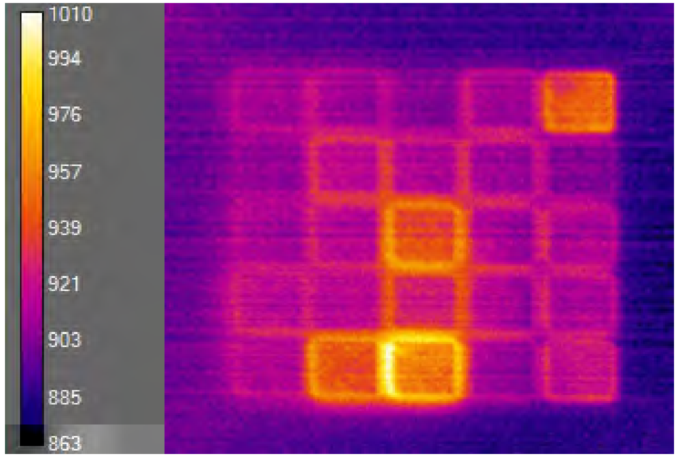


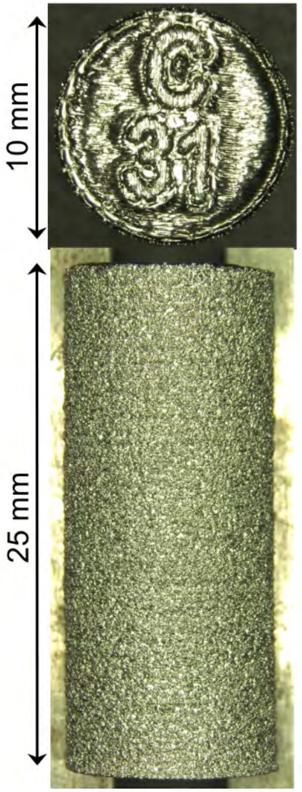
Westinghouse 3” x 3” Inconel 718
Fuel Nozzle, Build Time ~10.5 hrs

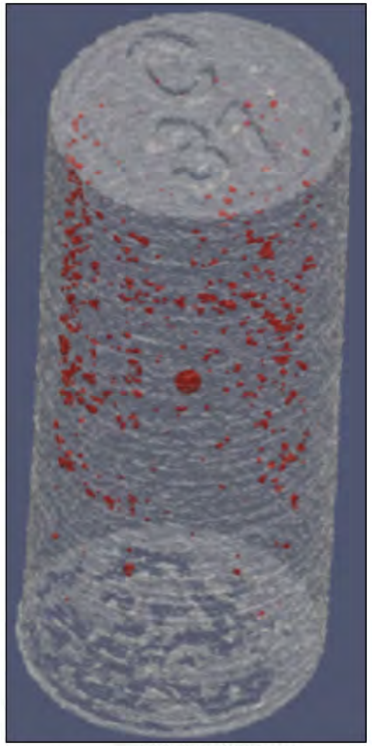
DOE/EPRI/Westinghouse/Rolls-Royce

Task 2: Process Design

- Components manufactured using **Renishaw® laser powder bed AM** processing equipment.
- The simple and complex geometries from Task 1 to be scaled & appended
- The process variables including: laser power, scanning speed, scanning strategy, preheat temperature, and powder characteristics will be recorded
- Three different qualities of build: poor, medium and high quality (intentionally) and compared.
  - Random defects, engineered defects, & with HIP.

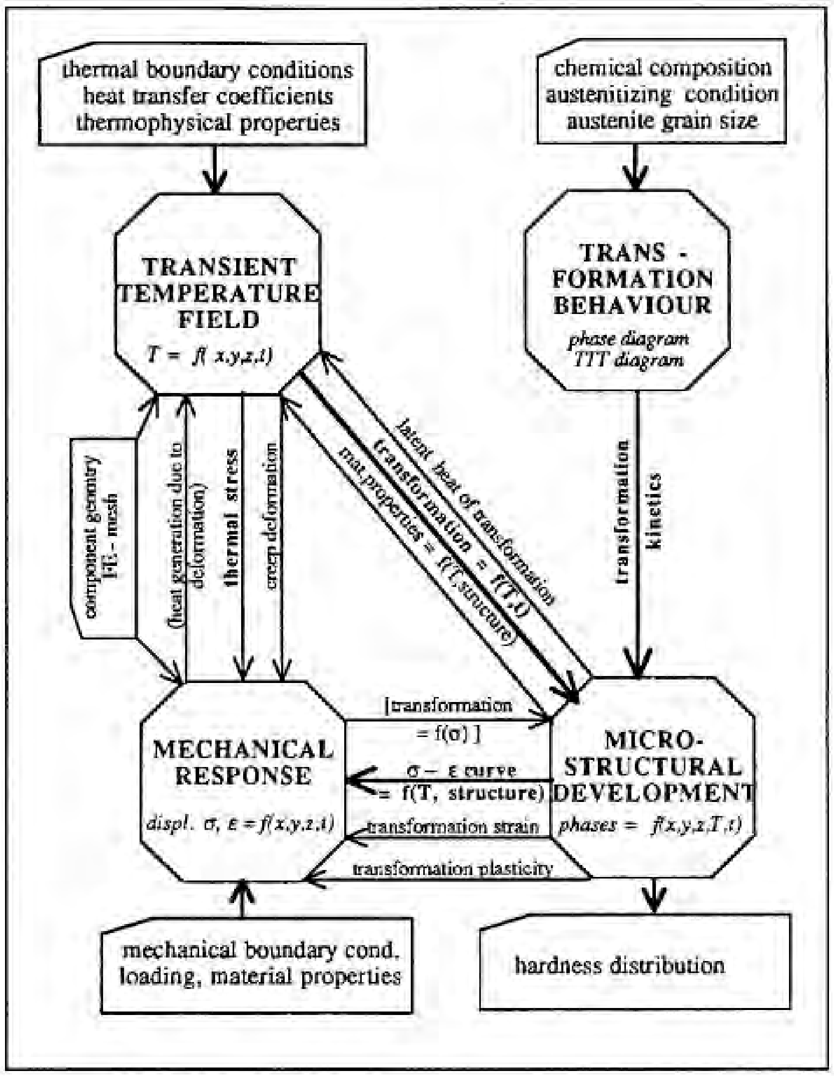






Task 3: Deploy and Validate High Performance ICME Computational Models (1)

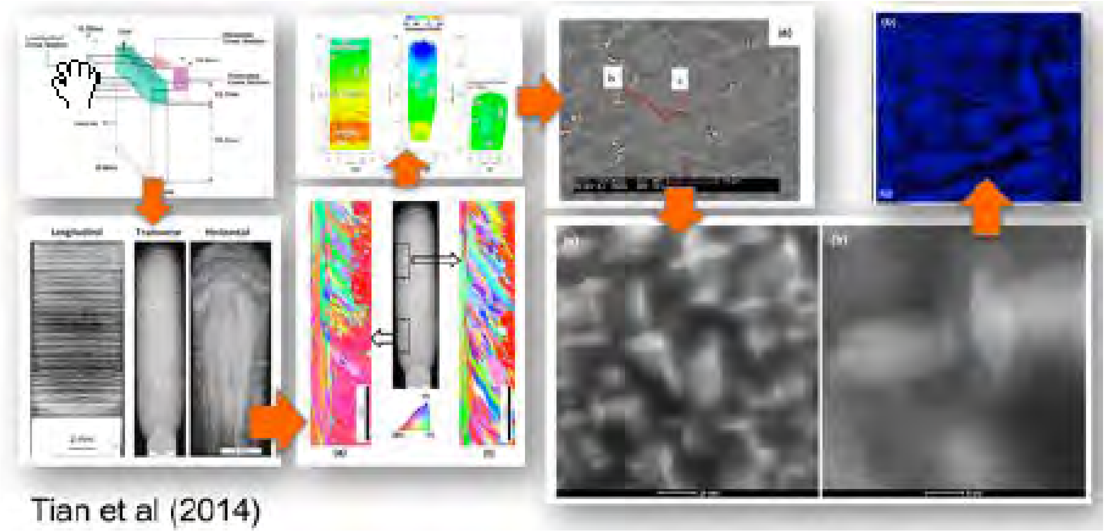
- Process parameter data and boundary conditions will be used as input for ICME models for heat transfer and mass transfer
- Models will be used to predict spatial variations of temperature, liquid metal flow, and liquid solid interface velocity.



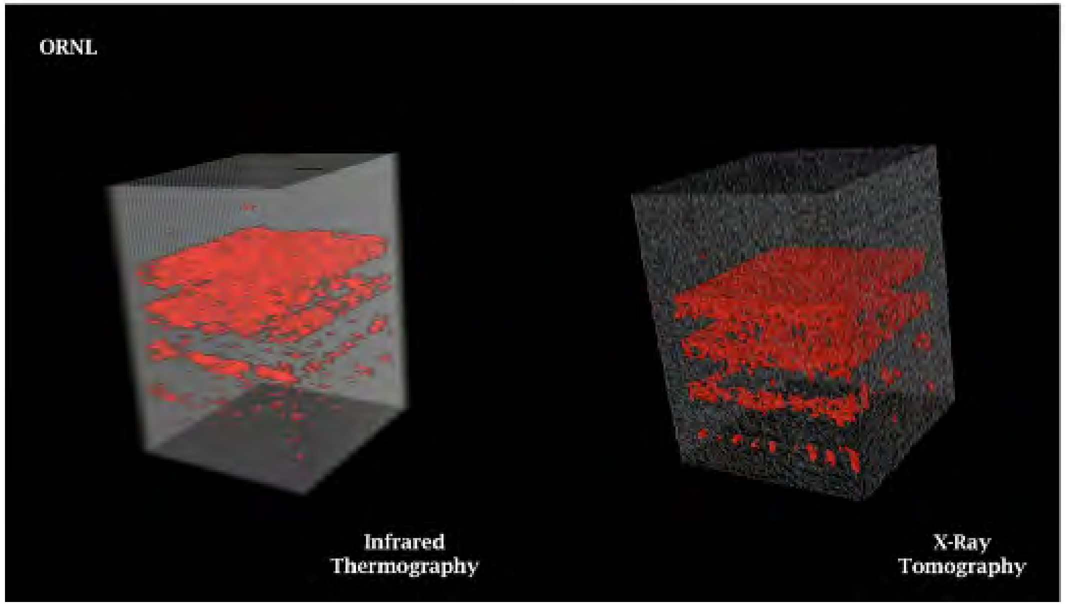
Task 3: Deploy and Validate High Performance ICME Computational Models (2)

- From these characteristics, models will be used to predict:
  - Defect formation
  - Columnar vs equiaxed grain deformation
- Predicted results will be validated from in-situ monitoring (Task 2)
- Data in turn will be loaded into 3D framework
- ICME models will be used to predict the debit of static, dynamic, corrosion properties

Task 4. Ex-situ NDE and Microstructural Characterization

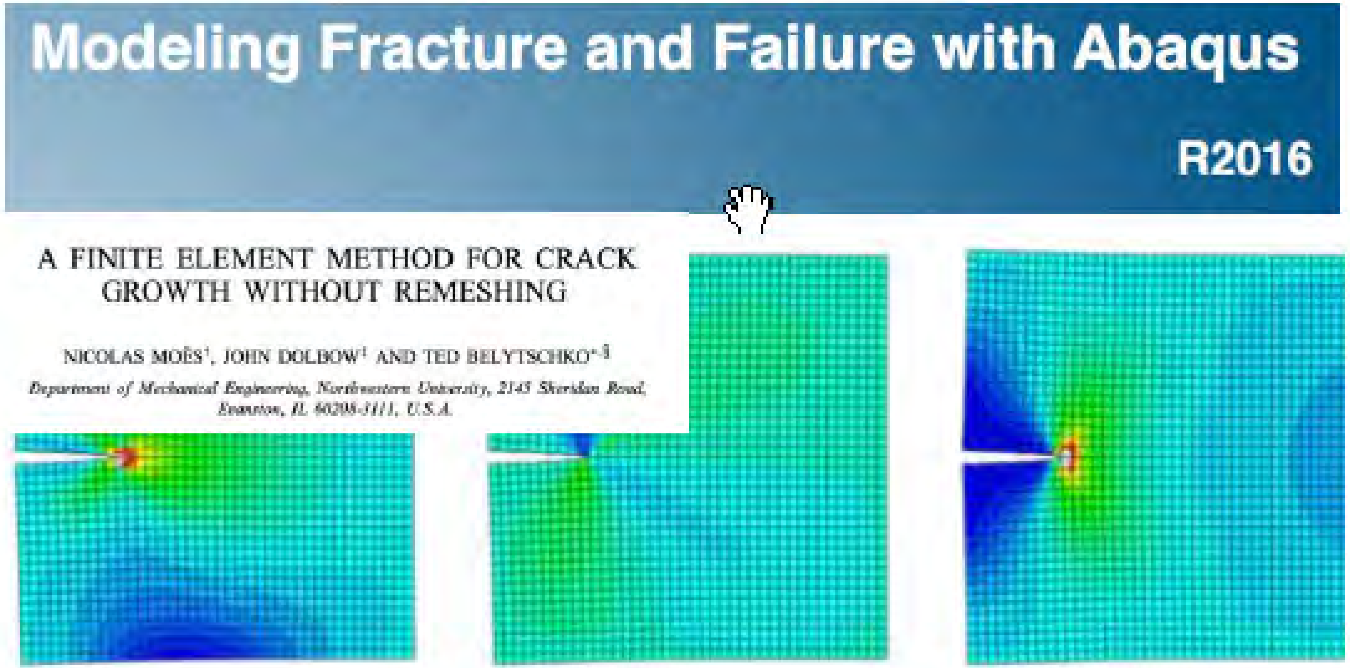


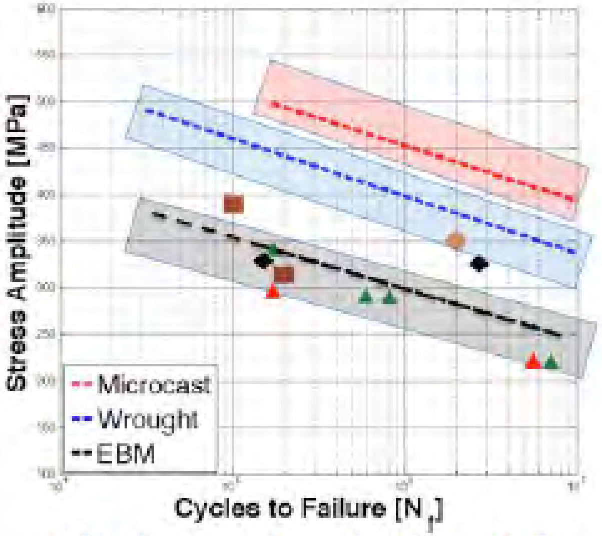
Multi-scale Characterization Methods (Optical, SEM, EBSD, TEM, etc



Comparison of Infrared Thermography and X-Ray Tomography Results

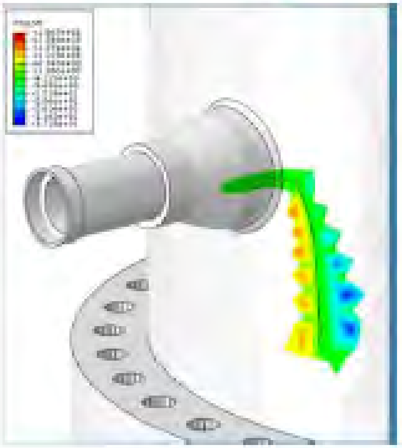
Task 5: Scale Up To Full Size Components

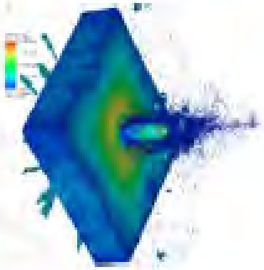


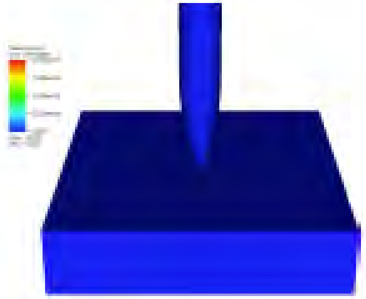


Kirka et al (2016)

- What can we do with this multitude of experimental and modeling datasets?



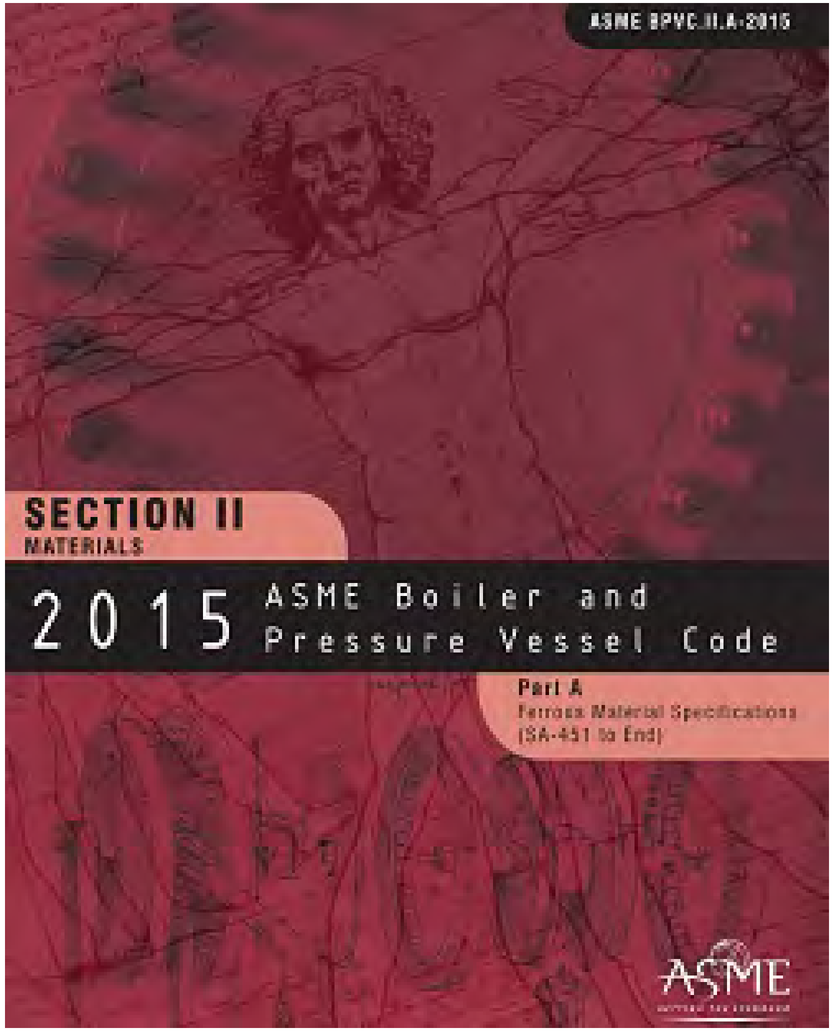




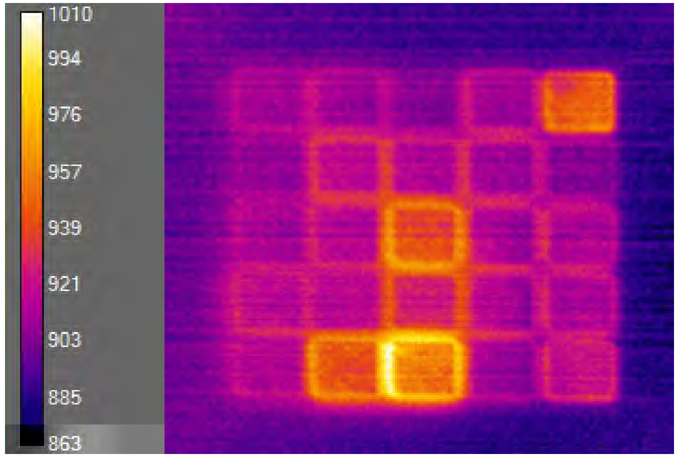
Simunovic et al (2013)

Task 6: Develop ASME Code Acceptance & Project Management

- If the ICME and in-situ process monitoring qualification methodology for AM components is proven correct, these methodologies will be documented for ASME Code and NRC acceptance.



Project Progress:
Task 2: Process Design



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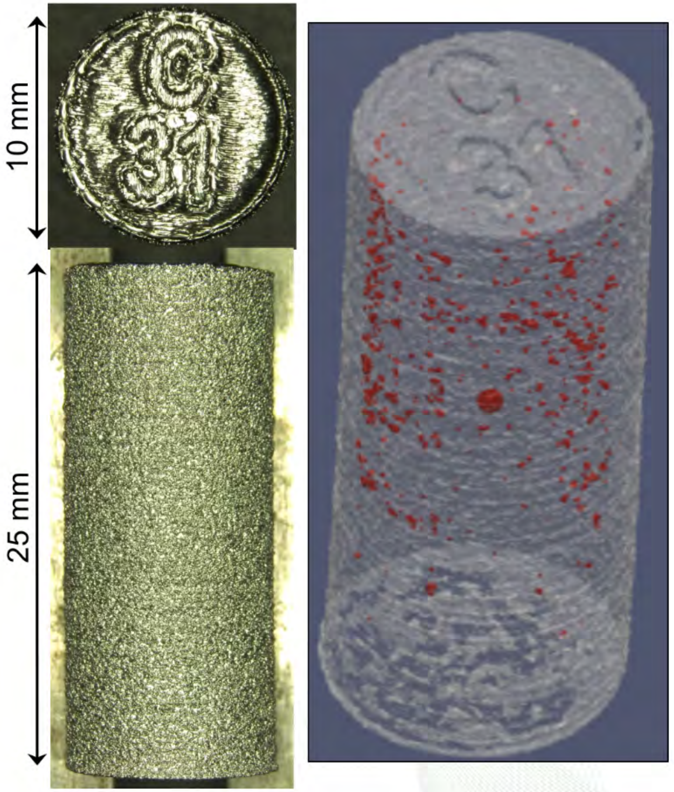
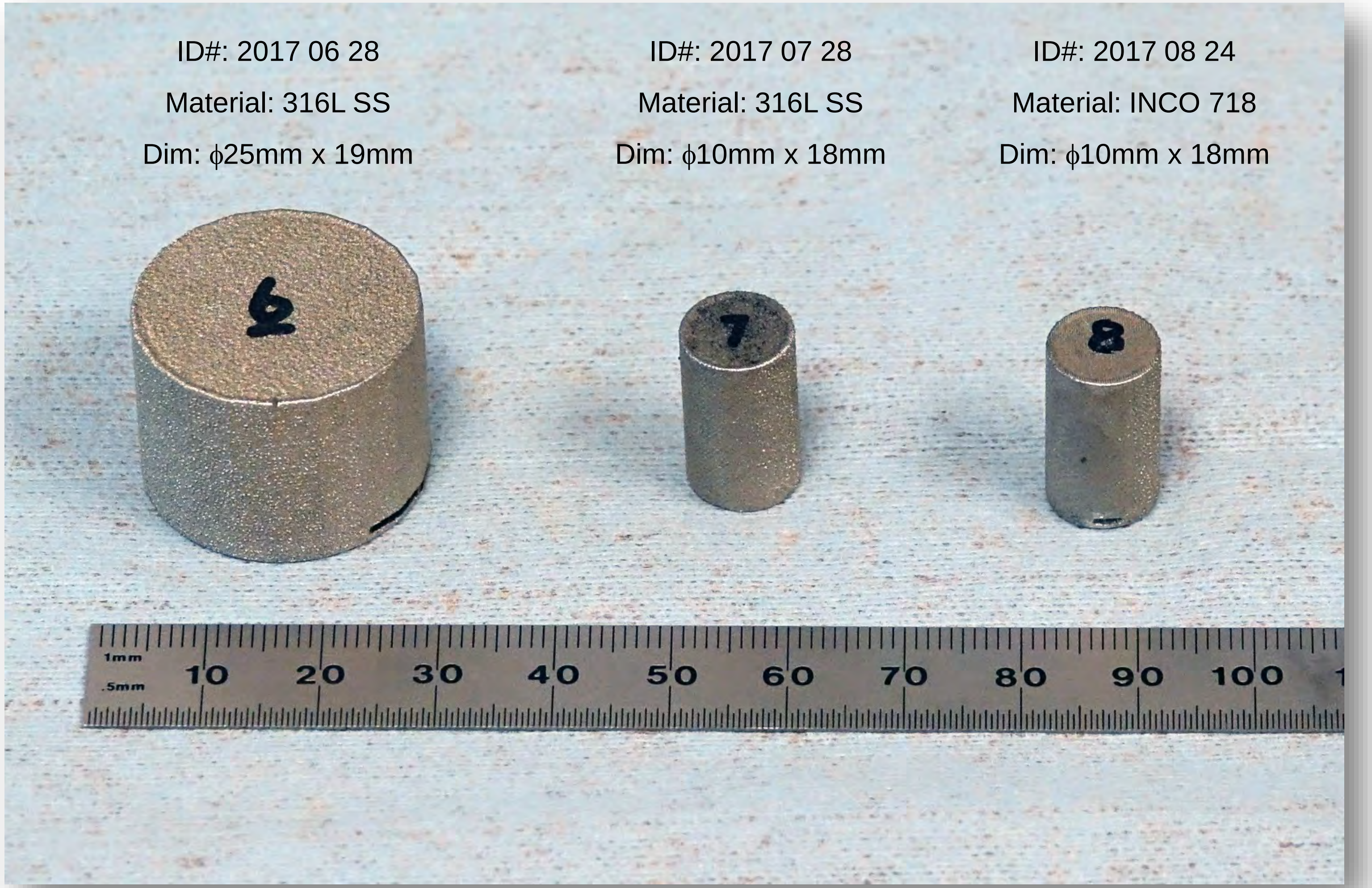


Three Cylindrical Samples Produced for CT Scanning

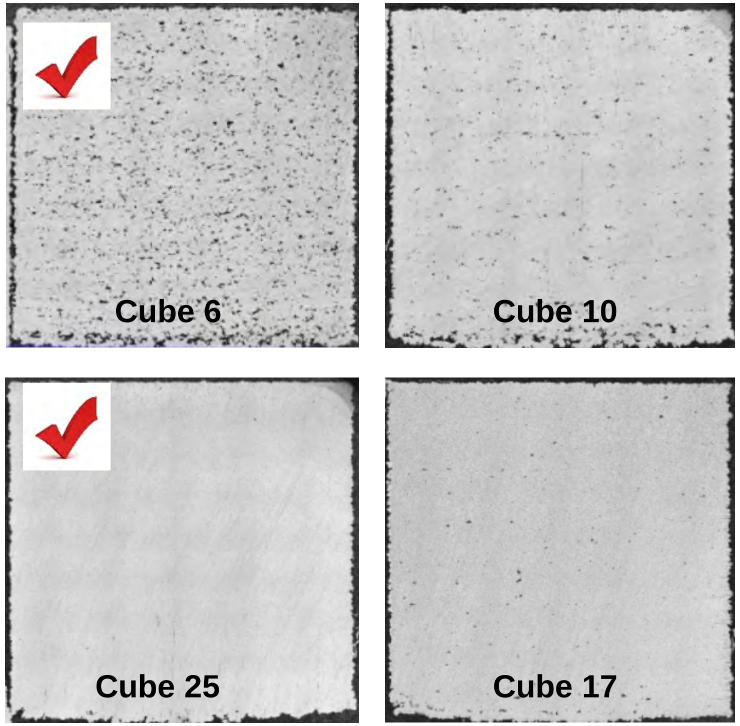
- Each sample contains both engineered and random defects
- IR data exists for each sample
- Goal: compare layer-by-layer IR data to the CT data.



Task 2: Process Design

- Developed a methodology to extract the defect generation probability from in-situ thermal imaging and analyses.
- **Key-factors:** time and spatial resolution
- **Key-findings:** There are critical data from maximum intensity, integrated area, pulses and time-decay
  - no need for IR to temperature conversion!

x-y plane cross-section



An Analytical Approach to Defect Mapping

- Over 1,000 frames are recorded for each layer.
- Cooling curves for each pixel within a layer are calculated from these frames.
- Comparison of cooling curves for each pixel are used to identify neighboring defects.

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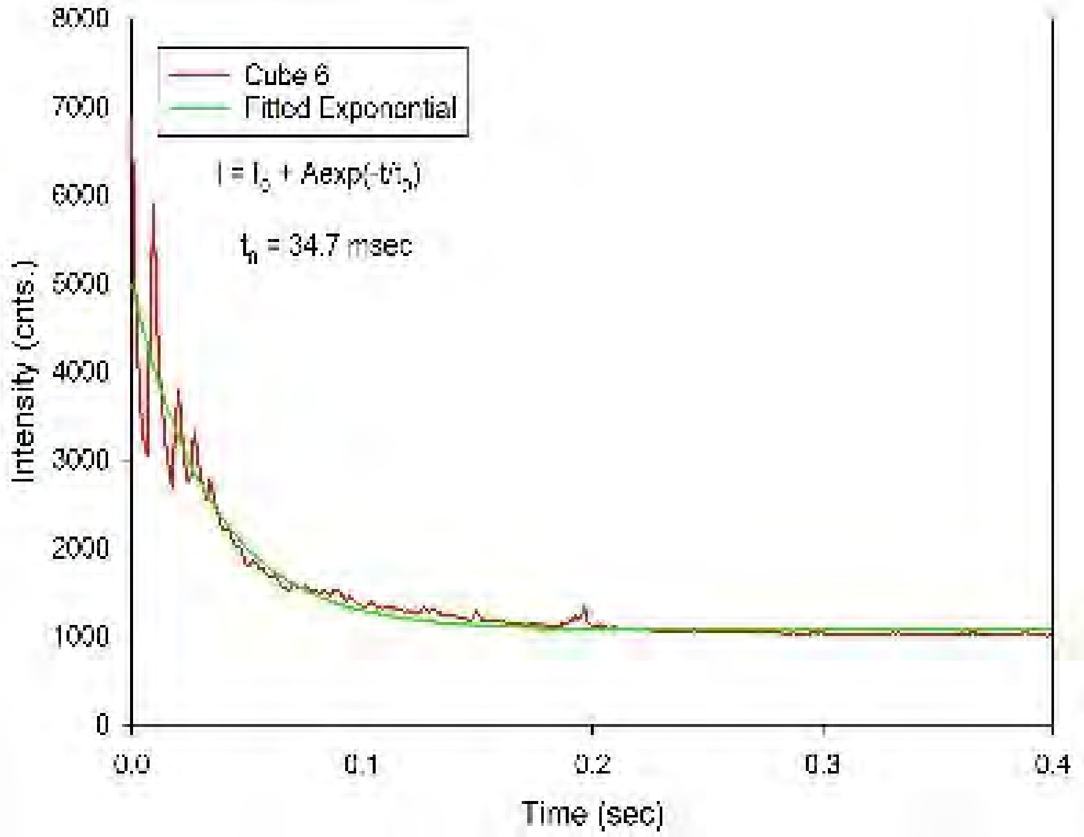
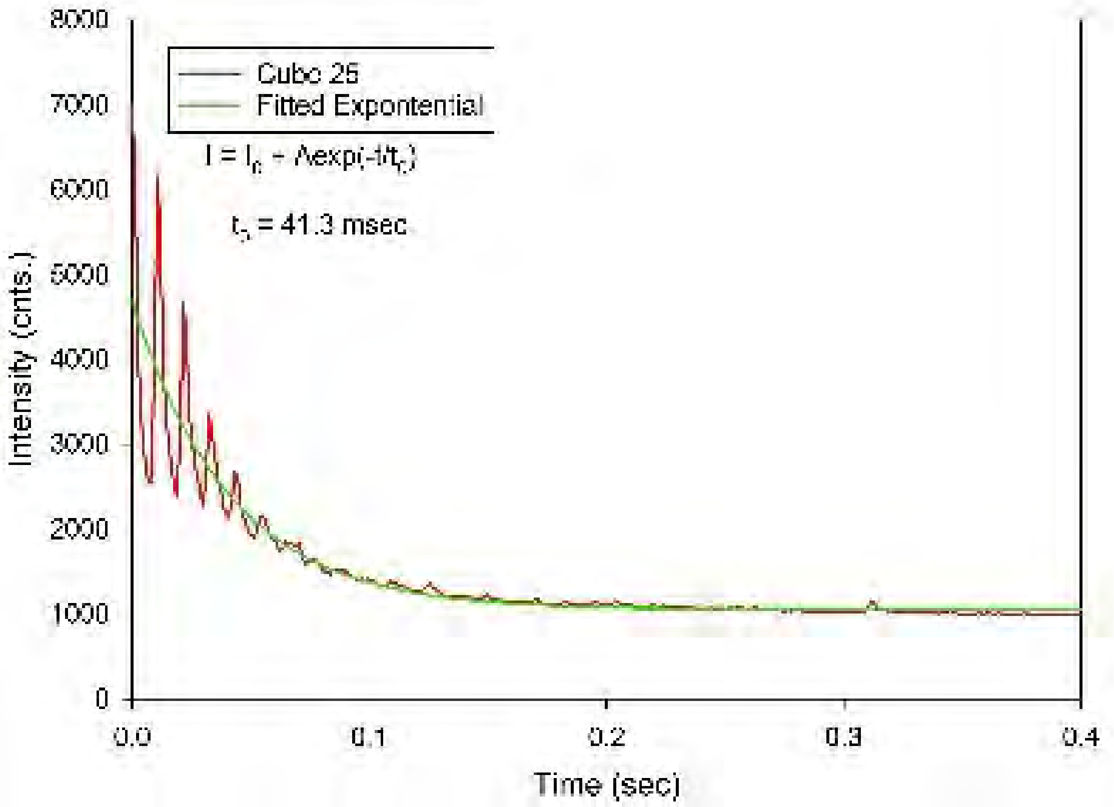
Task 2: Process Design

$$I(t) = I_0 + Ae^{-t/t_0}$$

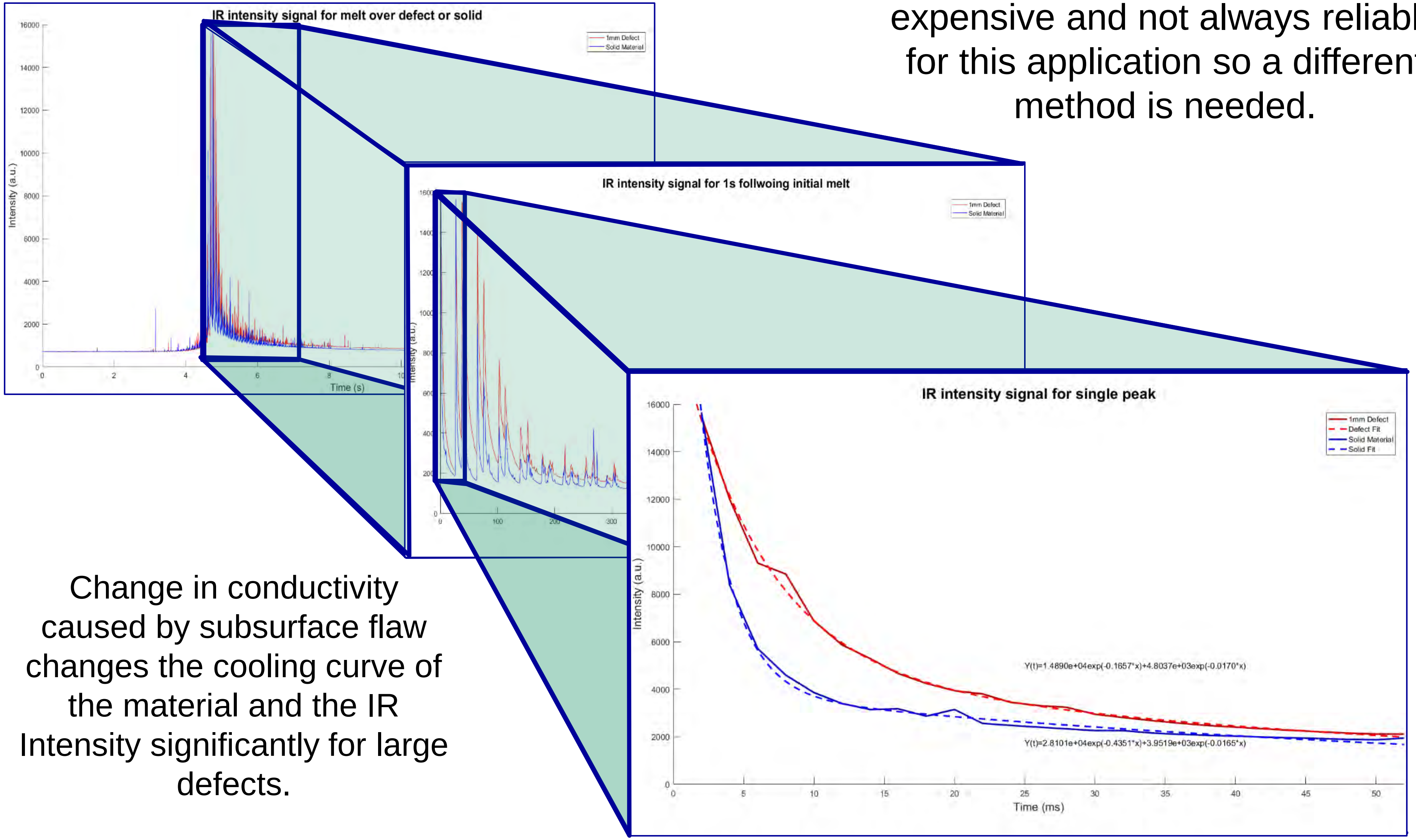




Raw IR Data

Data Analysis

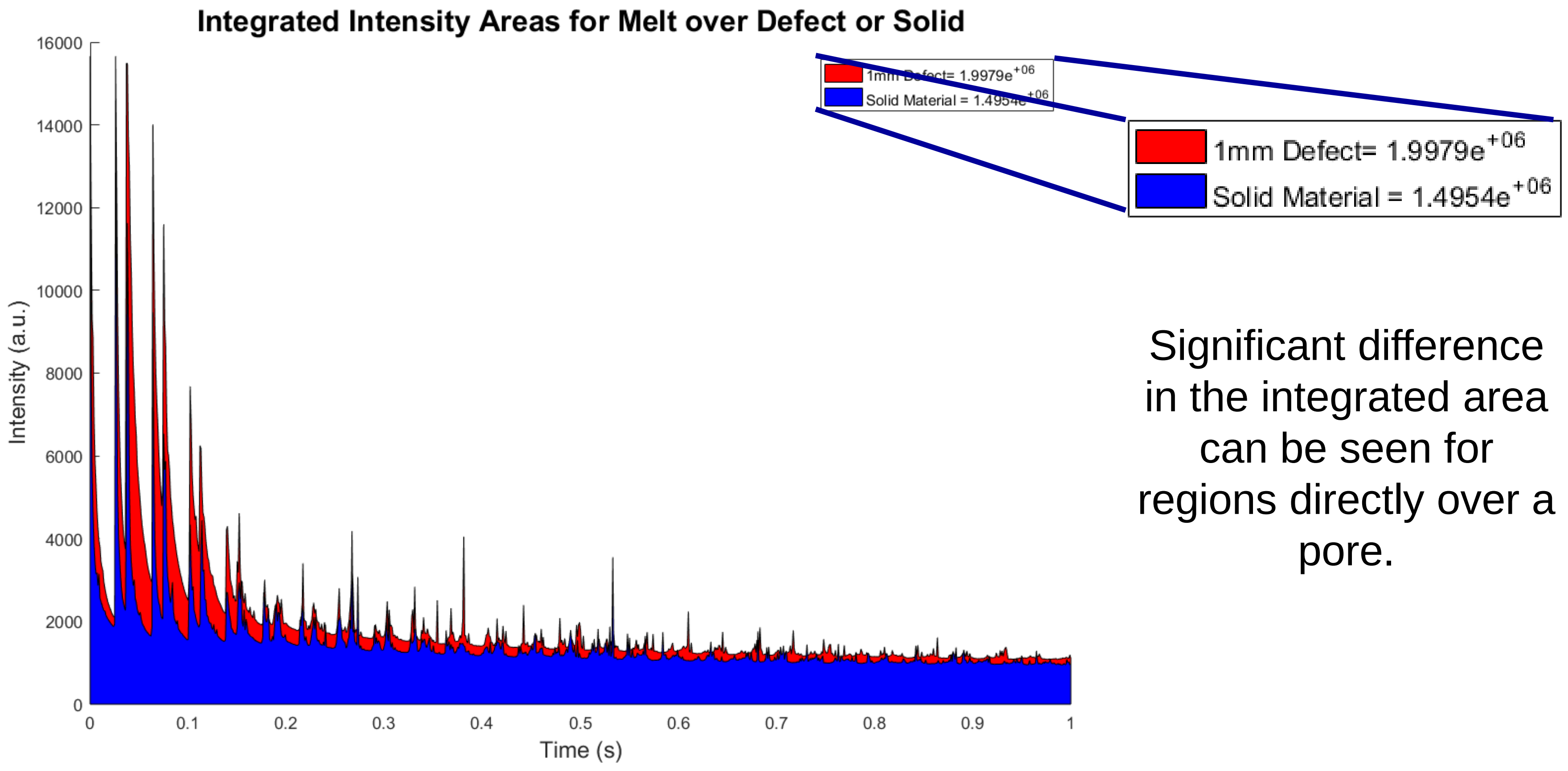
Curve fitting is computationally expensive and not always reliable for this application so a different method is needed.



Change in conductivity caused by subsurface flaw changes the cooling curve of the material and the IR Intensity significantly for large defects.

Integrated Intensity

- Taking the Area under the signal curve through integration allows for all of this information to be quantified by a single number. Showing any region where the signal has longer decay.

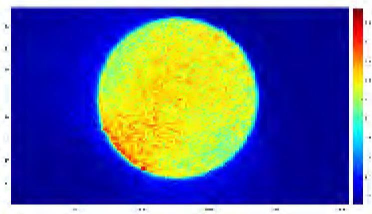


Significant difference in the integrated area can be seen for regions directly over a pore.

Thermal signature of porosity layers early in build process

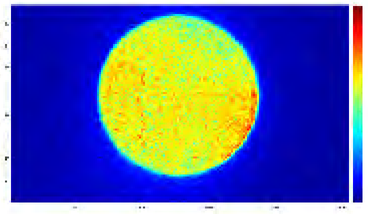
- Mapping Integrated intensity over entire surface reveals in-layer and subsurface flaws.

Layer 49



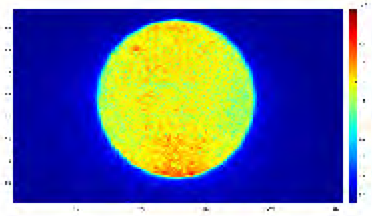
All voids visible in the layer

Layer 50



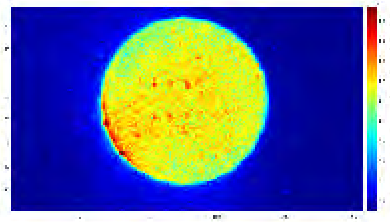
Far right voids melted, possibly remelted

Layer 51



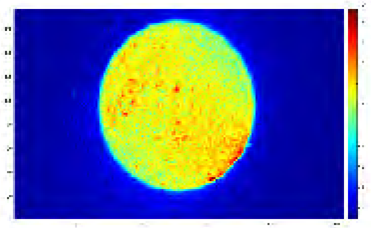
Next set of voids melted over

Layer 52



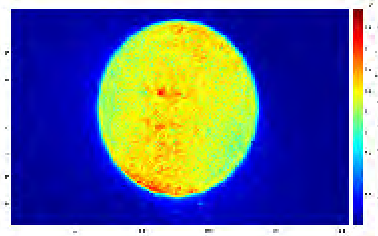
Two remaining rows of voids

Layer 53



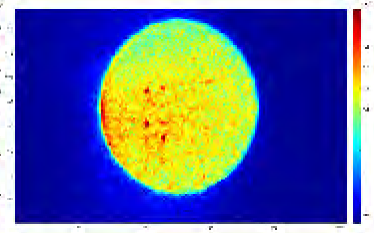
1mm voids remain

Layer 54

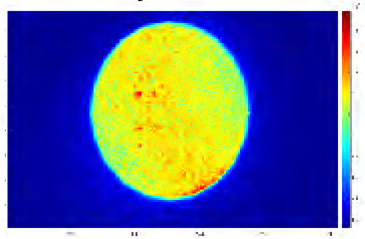


All voids melted over 1mm is most recent to be melted

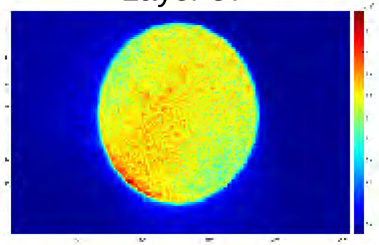
Layer 55



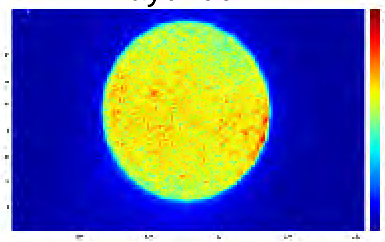
Layer 56



Layer 57



Layer 58



Some of the larger pores are still visible

- 200µm defects are not able to be detected because they are 1 pixel in measurement, 400µm defects can be detected in some layers depending on the thermal conditions.

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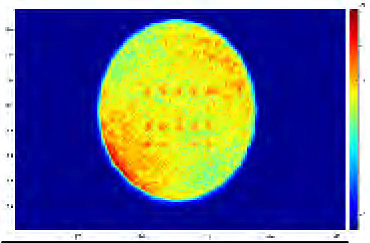
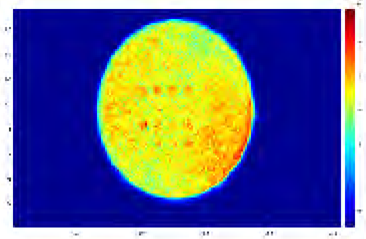
Thermal signature of porosity layers late in build process

Layer 350



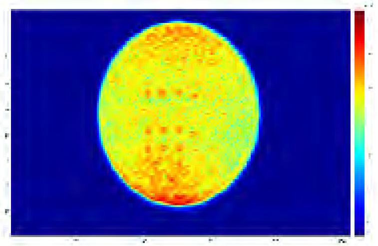
All voids visible in the layer

Layer 351



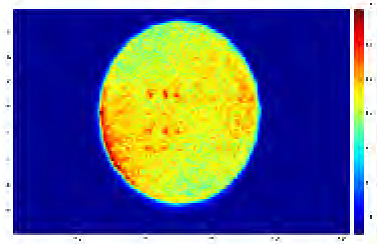
Far right voids melted, possibly remelted

Layer 352



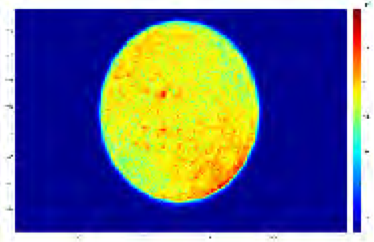
Next set of voids melted over

Layer 353



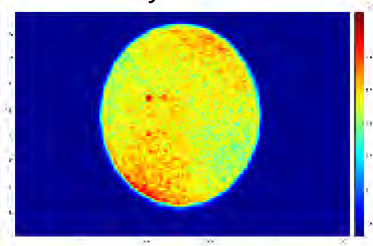
Two remaining rows of voids

Layer 354



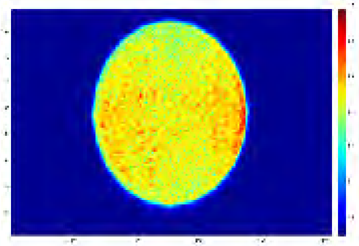
1mm voids remain

Layer 355

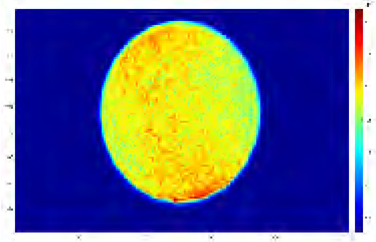


All voids melted over 1mm is most recent to be melted

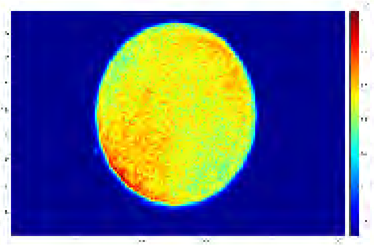
Layer 356



Layer 357

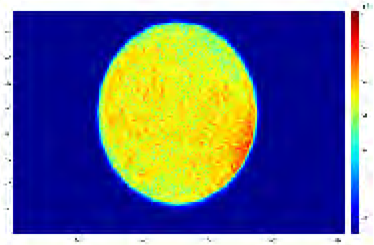


Layer 358



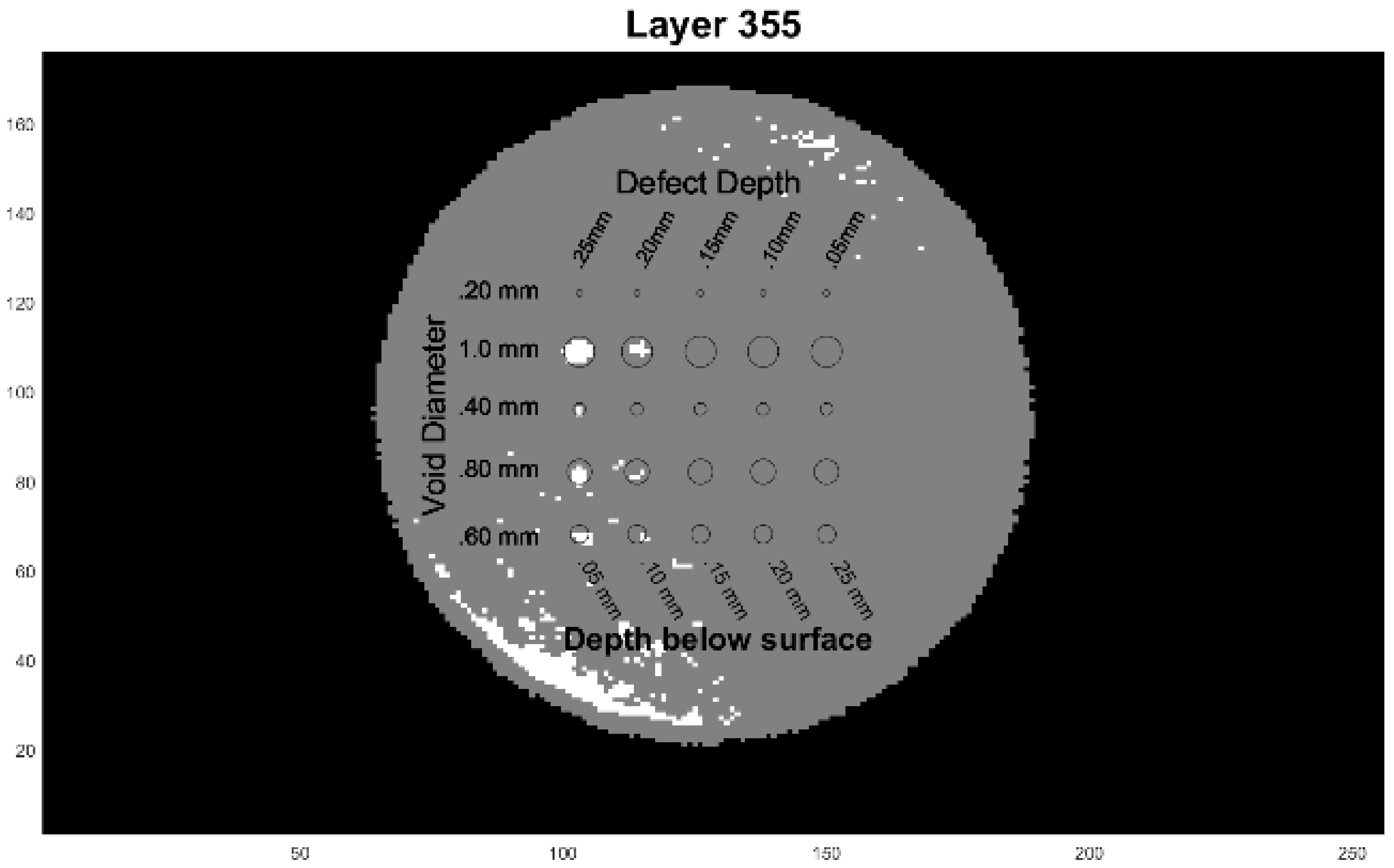
Some of the larger pores are still visible

Layer 359



No remaining visible voids

Detecting Potential Material Voids



Binarized images show the potential defect regions within the part

3D Visualization of Defects

What Have We Learned So Far…

- Using IR thermography and Data Analysis can provide a method to detect "in-layer" and "subsurface" defects that are sufficiently large enough for the camera resolution to pick up.
  - Beginning and end of melt path seem to show large increase as well
    - Not indicating defects however
  - Noise in the data caused by spatter also needs to be removed
    - Current impact of spatter is not as significant as beginning and ending melt regions
  - Produces terabytes of data
- Further analysis of high-resolution data is continuing.

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Major Deliverables Anticipated from the Project

1. Designs that will allow for LPB-AM of complex components
2. Fabrication of 3 components by AM, as well as, a traditional manufacturing processes
3. ICME process analytical methods to fuse the modeling, process, *in-situ* and *ex-situ* characterization data through Dream3d architecture
4. Data and ICME and *in-situ* process monitoring qualification methodology package to support ASME & regulatory qualification/acceptance.

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Project Summary

- Completed 1st year of 3-year project
- Believe we have developed IR monitoring method to capture defects (in-layer and subsurface).
  - Performing CT scans to fully characterize
  - 200µm flaw detectable
- Just starting the ICME computational modeling part of the project and ex-situ characterization.
- Beginning engagement with ASME and Regulators
- Terrific engagement by industrial partners: WEC and Rolls-Royce.

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Project Schedules and Milestones Status

Task	1	2	3	4	5	6	7	8	9	10	11	12	Org.
1. Design													OEM
2. Processing & In-Situ Analyses													Nat Lab
3. Computational Modeling													Nat Lab
4. Ex-situ Characterization													OEM
5. Scale Up													OEM
6. Regulatory & Code Acceptance													PI

Project Milestones will include: 1). Fabrication of three nuclear parts via AM; 2). Collection of ICME and in-process monitoring data (data package); 3). Transfer of monitoring technology directly to the two participating OEMs for immediate implementation and use; 4). Ex-situ characterization assessment data along with scale up information; and 5). ASME Code Case submittal for nuclear qualification of AM.