MSFC
Additive Manufacturing
Nondestructive Evaluation Efforts

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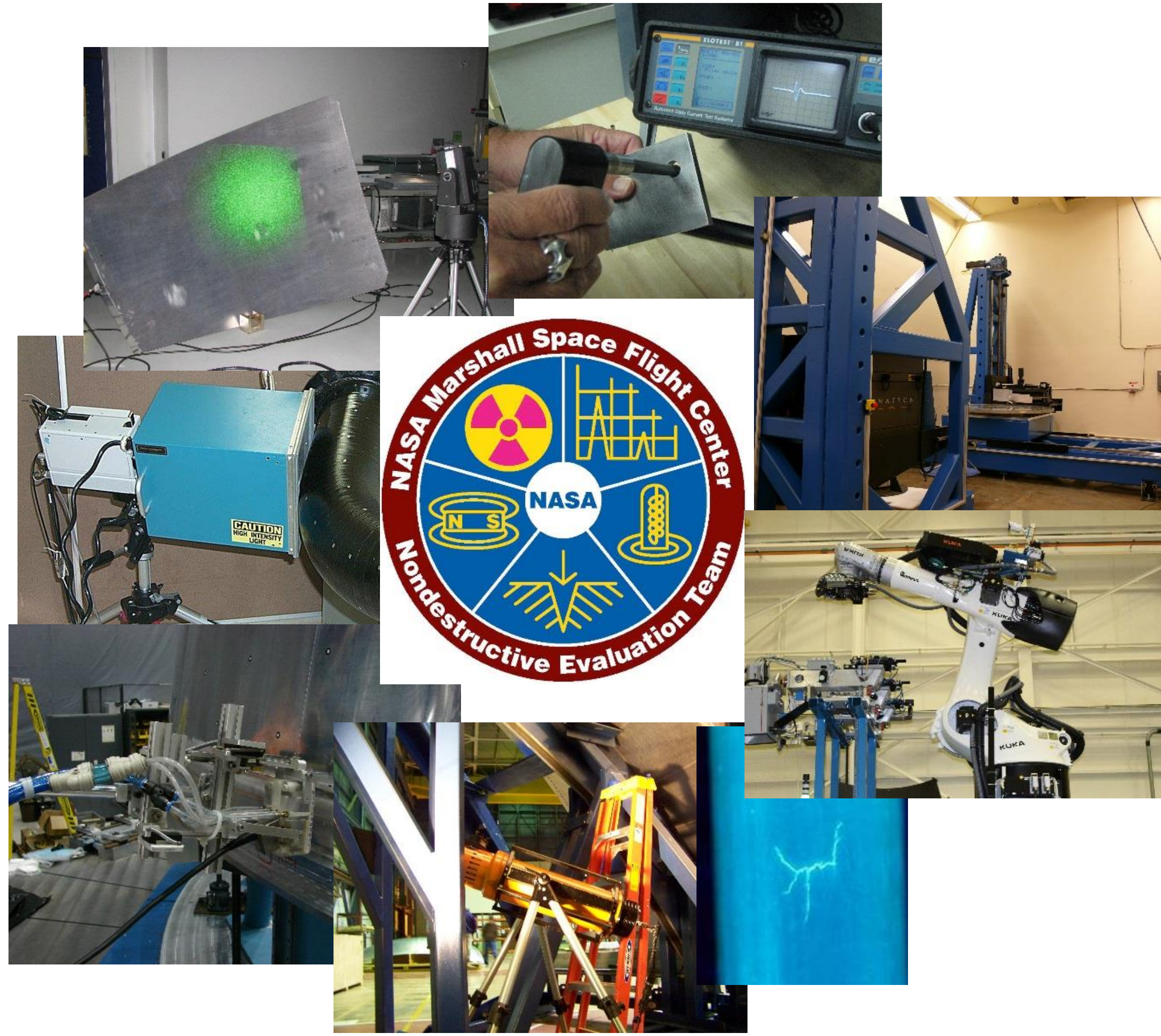
MSFC NONDESTRUCTIVE EVALUATION CAPABILITY OVERVIEW

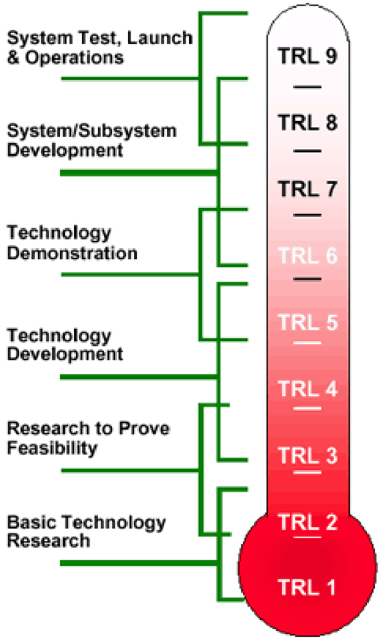
MSFC NONDESTRUCTIVE EVALUATION

- Liquid Penetrant
- Eddy Current
- Ultrasonics
  - Phased array
  - Immersion
  - Contact
  - Air coupled (Limited)
- Radiography
  - Digital
  - Film
- Magnetic Particle
- Computed Tomography
- Thermography
- Shearography
- Acoustic Emission



MSFC NONDESTRUCTIVE EVALUATION

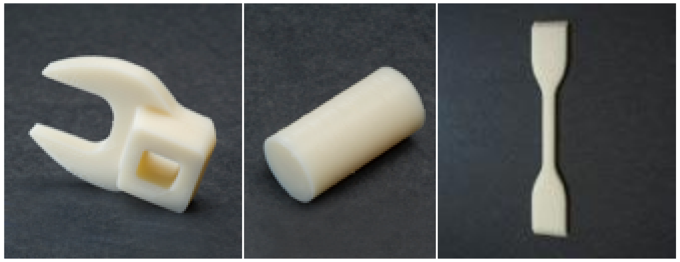
- Facilities and personnel primarily focused on working projects in the technology readiness level (TRL) 4-8 range.
  - ➢ Technique development of existing methods on new hardware
  - ➢ Work with and assist the Project Offices with their Prime Contractors to plan and implement the appropriate level of NDE and damage tolerance. Assess gaps between contractual requirements and contractor practices, providing data for risk assessments.
    - ✓ Space Launch System (SLS)
    - ✓ Commercial Crew
- Ability to deploy across the country with most methods to go to the part when it is not feasible to bring it on-site.
- Personnel (17 total)
  - ➢ 10 civil servant engineers
  - ➢ 1 civil servant technician
  - ➢ 2 contractor engineers
  - ➢ 4 contractor technicians
- Certifications held
  - ➢ ET, PT, MT, RT, UT, IRT (LII and LIII)
  - ➢ PE

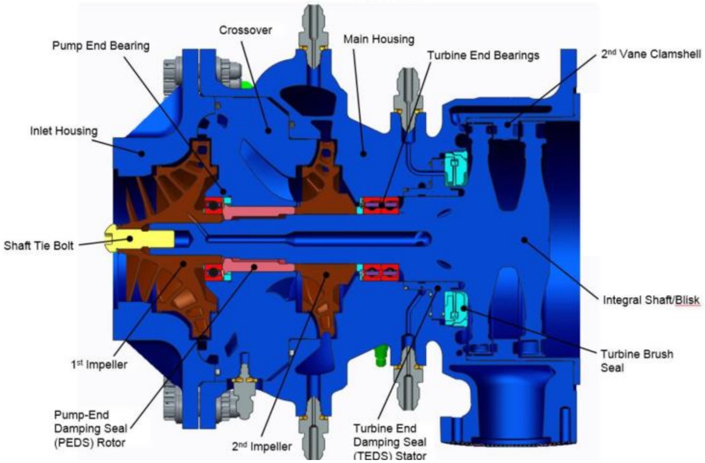


MSFC NDE TEAM AM RELATED WORK

NDE TEAM AM RELATED WORK

- Space Launch System (SLS) Liquid Engines Office
  - Working with our commercial partner on their additive manufacturing initiatives for the SLS RS-25 Block Upgrade
- Made-in-Space
  - Performed an assessment of CT data from plastic parts made on the International Space Station versus parts made with the same system and parameters on Earth.
- AM Demonstrator Engine Block 1 Liquid Hydrogen Turbopump
  - Performed CT, RT, PT and ET between hot-firings
- Blown Powder Welding
  - Performing PT, RT
- MSFC AM Development
  - Assessing detection capability for critical defects
  - Effects of unique characteristics of Selective Laser Melting (SLM) on conventional NDE
    - ✓ Penetrant, radiography, ultrasonics, eddy current
  - Effects of unique characteristics of SLM on CT
    - ✓ Energy/penetration versus detection resolution
  - CT dimensional assessment/defects
  - Understanding what defects are fracture critical
  - In-Situ NDE and process control





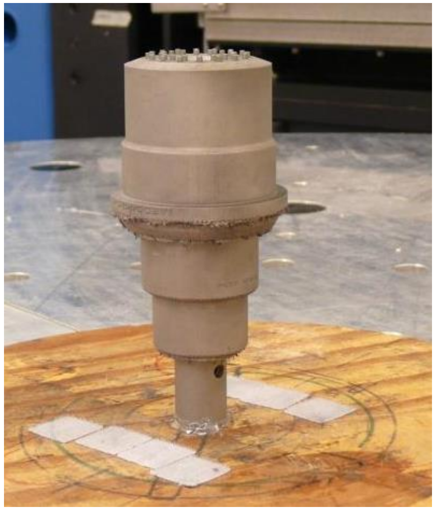
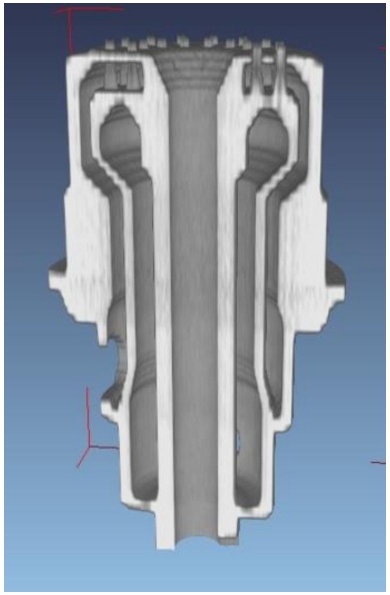
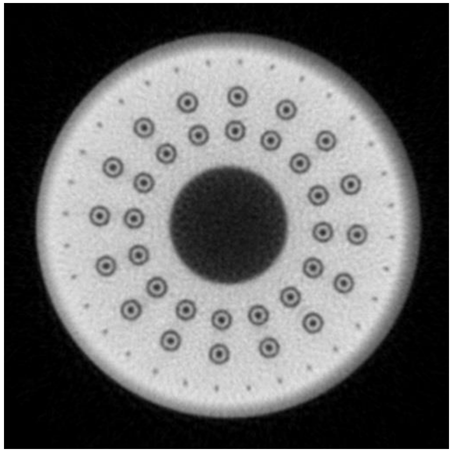
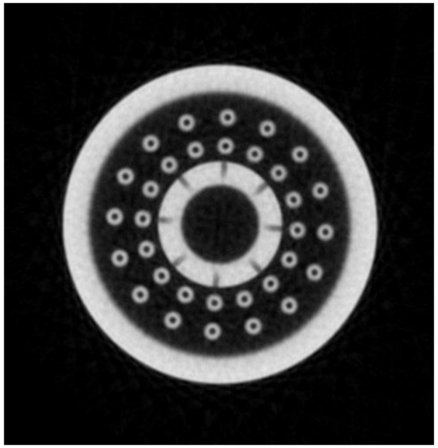
NDE TEAM AM RELATED WORK

- NASA Funded Projects
  - Advanced Developments Office funded research
    - ✓ Characterization of Direct Metal Laser Sintering Materials for Space Launch System Engine Components (2013)
    - ✓ Computed Tomography Sensitivity Verification for Selective Laser Melting SLS Engine Components (2015)
  - Office of Safety and Mission Assurance NDE Program Funded Research
    - ✓ An Assessment of NDE Capability and Materials Characterization for Complex Additive Manufacturing Aerospace Components (2015-16)
    - ✓ A Quantitative Assessment of NDE Capability on Additive Manufactured IN718 (2017-current)
    - ✓ In-Situ Monitoring of Additive Manufacturing (Proposed for 2020)

- ASTM Involvement
  - F42 Additive Manufacturing
    - ✓ 4th Symposium on Structural Integrity of Additive Manufacturing – Washington D.C., Oct. 2018
    - ✓ 1st Additive Manufacturing Center of Excellence Workshop – Auburn, March 25th, 2019
    - ✓ 5th Symposium on Structural Integrity of Additive Manufacturing – Washington D.C., Oct. 2019
  - E07 Nondestructive Evaluation
    - ✓ WK47031 – Standard Guide for Nondestructive Testing of Additively Manufactured Aerospace Parts After Build
    - ✓ WK62181- Standard Guide for In-Situ Monitoring of Metal Additively Manufactured Aerospace Parts

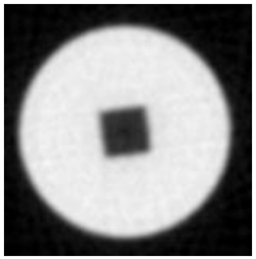
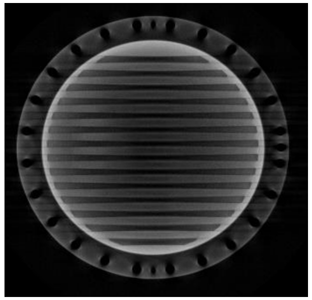
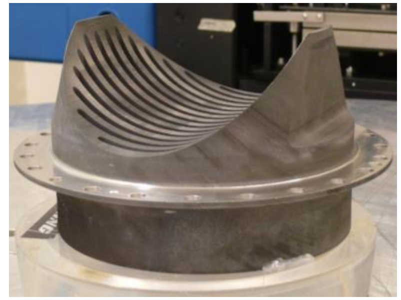
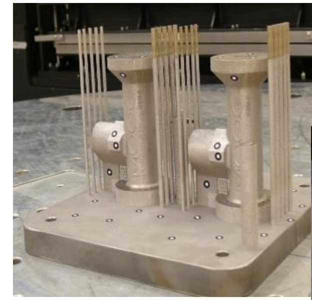
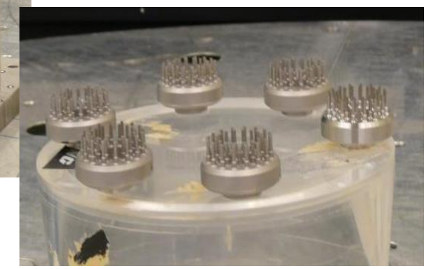
Design for AM ≠ Design for inspectability

The AM technology is only cost effective if it is used to make parts that can't be made easily by normal machining processes, so AM parts typically have complex geometries

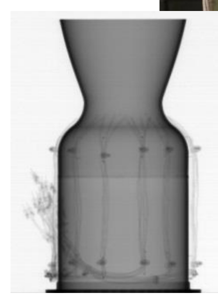
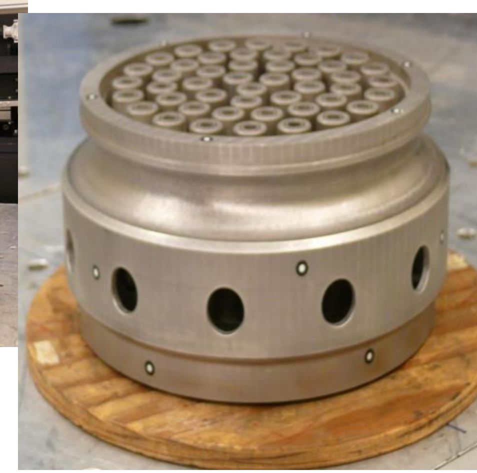
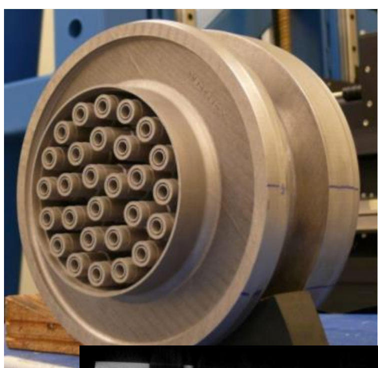
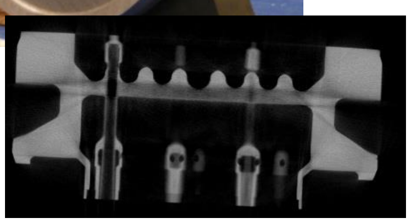





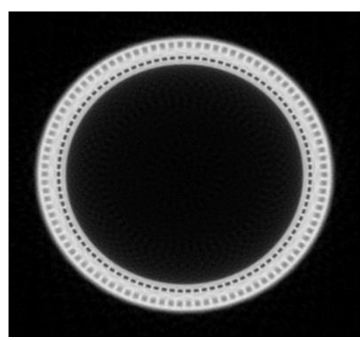
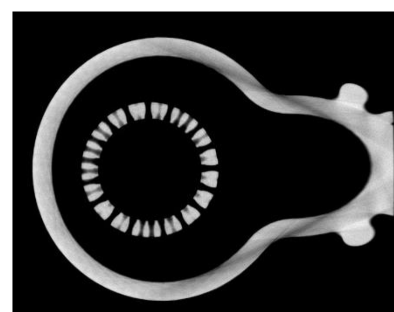
AM ENGINE RELATED COMPONENTS

Examples of sizes and shapes of AM parts targeted
Primarily IN718 and GRCop 42



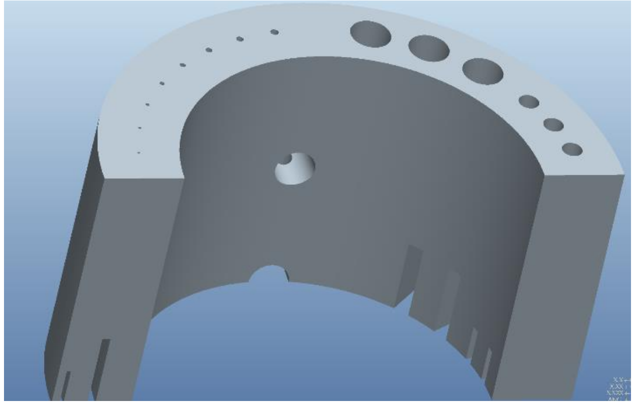

SOME QUESTIONS ABOUT NDE OF AM COMPONENTS

- Can NDE be used to provide dimensional assessments of hidden features?
- How does conventional NDE perform on AM components?
  - ✓ Are the tables in NASA-STD-5009 applicable to AM components?
- How do you make controlled defects in AM components?
- How will hidden areas be inspected?
- Does it make a difference for NDE if the part is "green", stress relieved, or fully heat treated?
- Are there opportunities to catch defects as the component is being fabricated or at least highlight suspect areas?

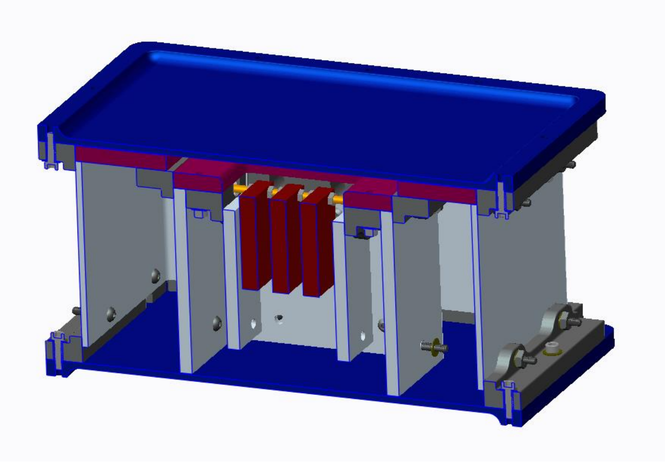
OVERVIEW OF A FEW AM NDE EFFORTS

CT DIMENSIONAL ASSESSMENT

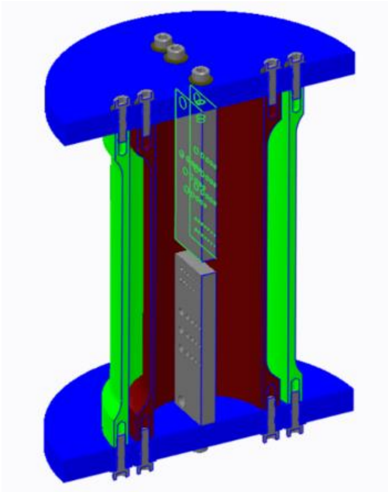
- Purpose: Develop reference standards for assessing the dimensional accuracy and defect detection capability of CT for large complex AM components
- Goal: Provide flexibility to simulate features of large complex AM components without having to build a new reference standard for every unique structure



Gage Block



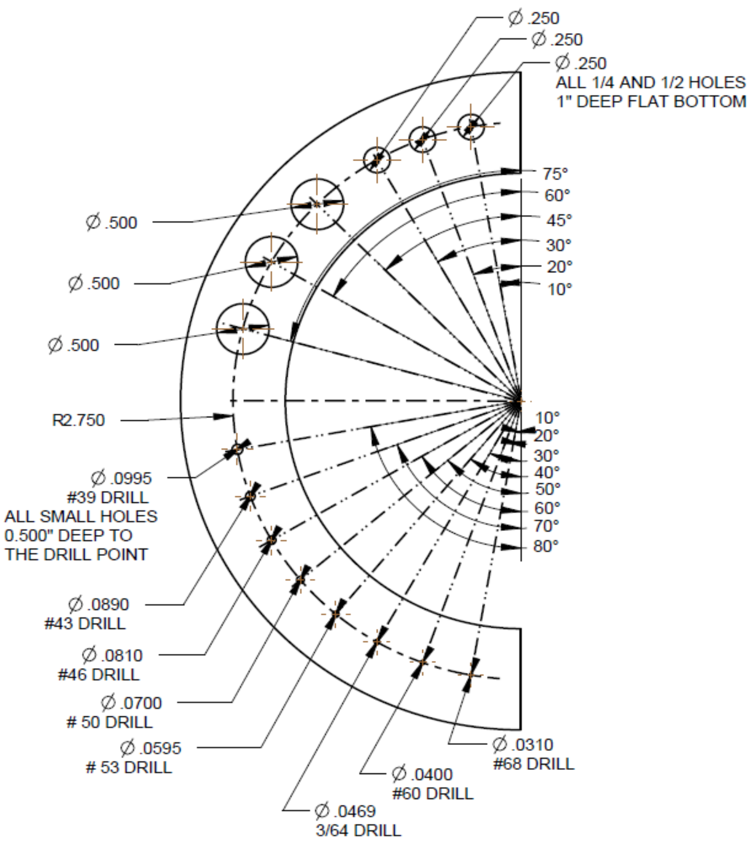
Box Modular Reference Standard

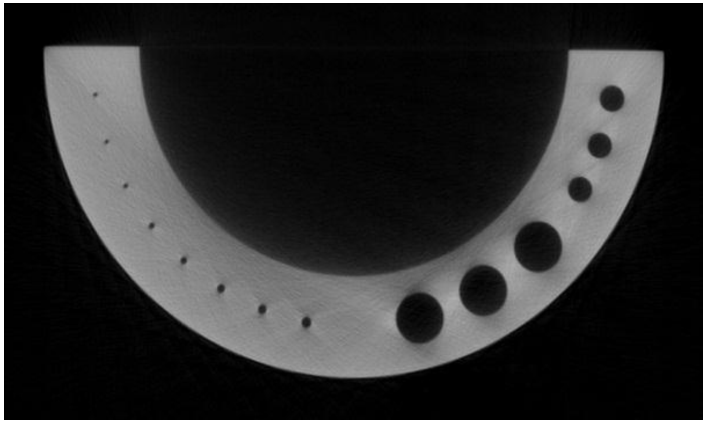


Circular Modular Reference Standard

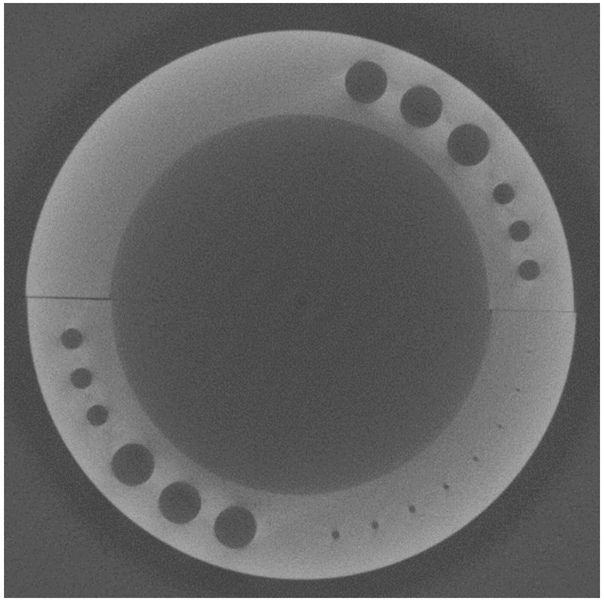
GAGE BLOCKS

- Designed with a range of features and sizes to test CT capabilities
- Made to simulate large AM components
- Four gage blocks fabricated (Aluminum/Inconel 718; Additive/Wrought)



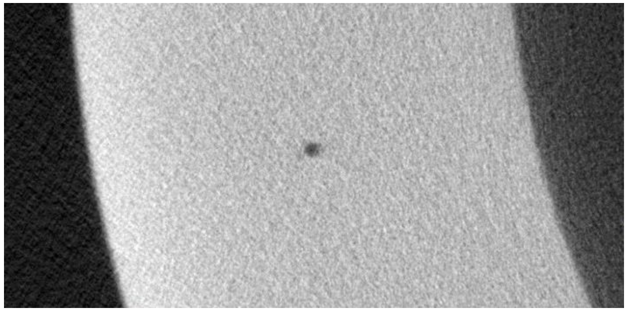


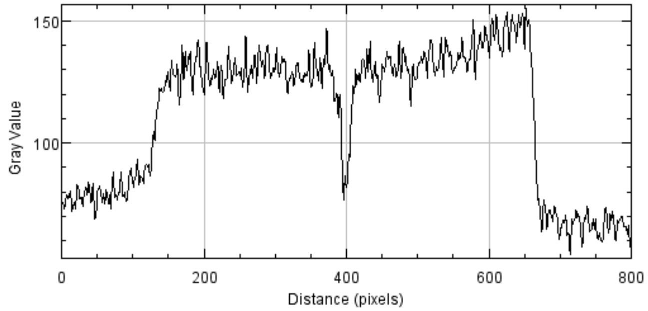
2 MeV CT (Inconel 718)



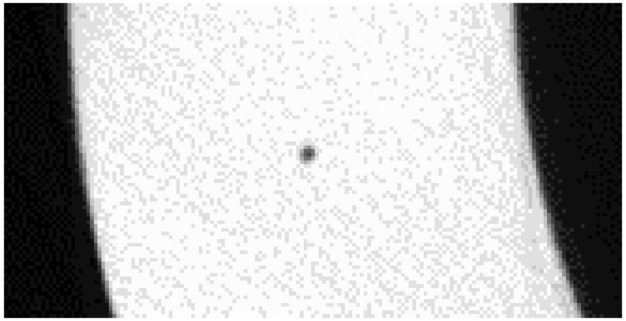
225keV micro-focus CT (GRC) (Aluminum)

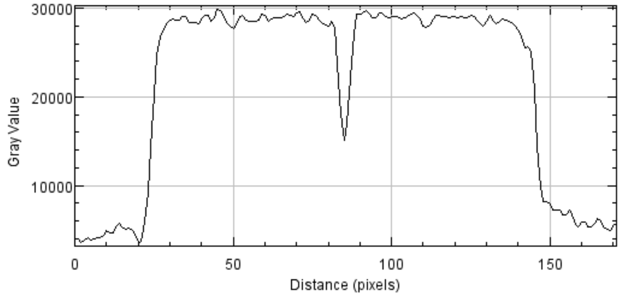
GAGE BLOCKS (Sample results)





225 keV CT system (GRC) SNR = 22.2



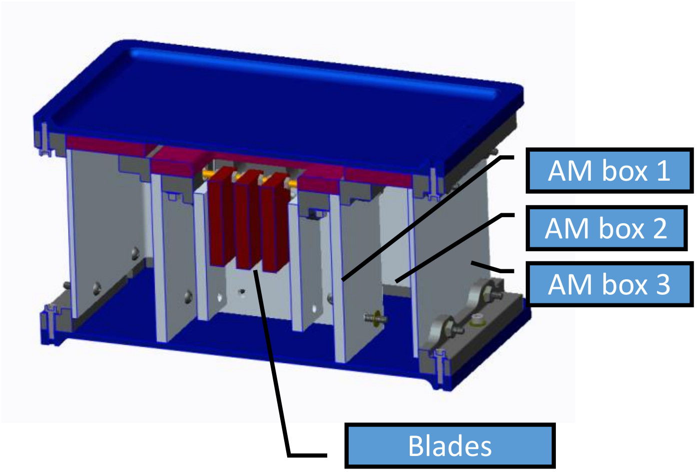


2 MeV CT system SNR = 47.1

- Line profiles across the smallest holes and signal-to-noise ratios (SNR) in the wrought aluminum blocks show that both systems detected the hole, while the higher energy system produced a less noisy image.
- Errors between as-built and CT measured hole diameters seen to vary with diameter.

Inconel		Additive		
Drawing Location	Measured (SLM) mm	CT measured	2nd Gen SLM Error mm	**2nd Gen SLM % Error**
A	0.7153	0.981	0.2657	**37.1394**
B	0.8478	1.09716	0.2494	**29.4139**
C	1.0045	1.2432	0.2387	**23.7642**
D	1.4436	1.6848	0.2412	**16.7101**
E	1.7891	1.7275	-0.0616	**-3.4437**
F	2.0731	2.0606	-0.0125	**-0.6053**
G	2.2873	2.3302	0.0429	**1.8755**
H	2.5365	2.5081	-0.0284	**-1.1212**
				12.9666

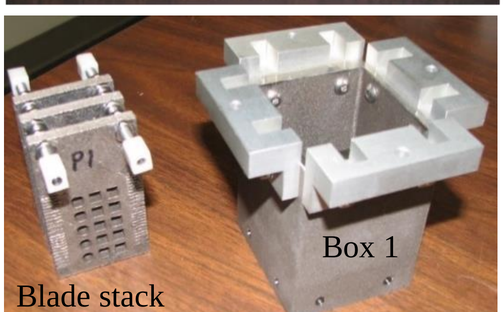
BOX MODULAR REFERENCE STANDARD

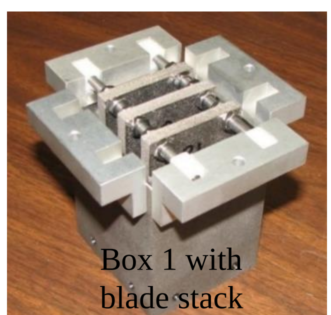


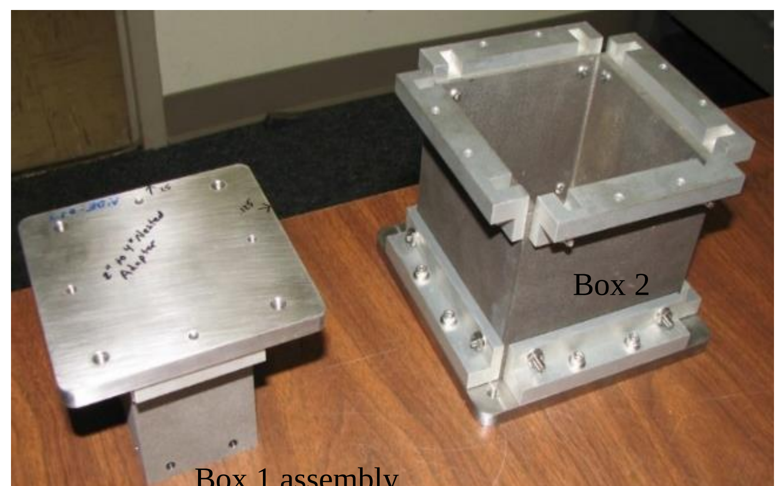
- ➢ Ability to insert "blades" with features of interest
  - ✓ Geometric features (holes, notches, dimensional, etc)
  - ✓ Defect features (cracks, porosity, trapped powder, etc)
- ➢ Ability to build blades with features without the risk of losing the entire part
- ➢ Ability to increase or decrease the complexity, degree to which the blades are hidden
  - ✓ 1, 2 or 3 shell layers
  - ✓ 2 opposite walls are .125" and .250" thick
- ➢ Ability to create a "blind" test standard by attaching endplates
- ➢ Ability to inspect individual components with traditional NDE methods
- ➢ Ability to use box to demonstrate NDE in "tight" confines


Blades

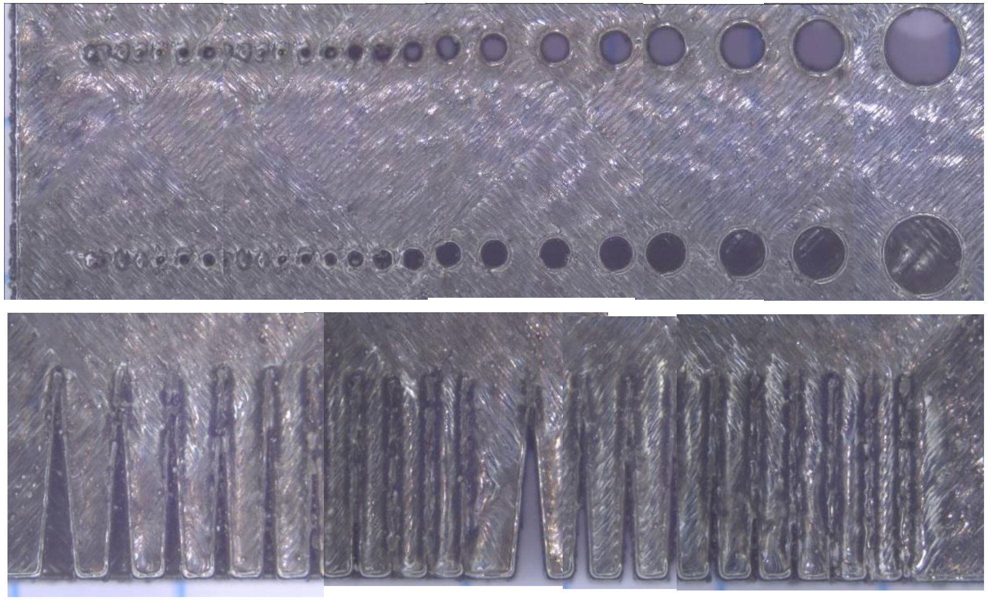
Box 1: 2.25" x 2.5" x (1/8" and 1/4") wall
Box 2: 4.25" x 4.5" x (1/8" and 1/4") wall
Box 3: 8.25" x 8.5" x (1/8" and 1/4") wall


Blade stack
Box 1

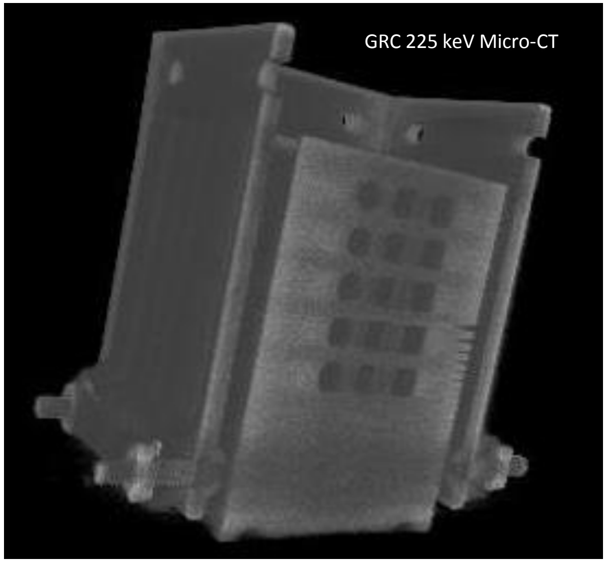

Box 1 with blade stack

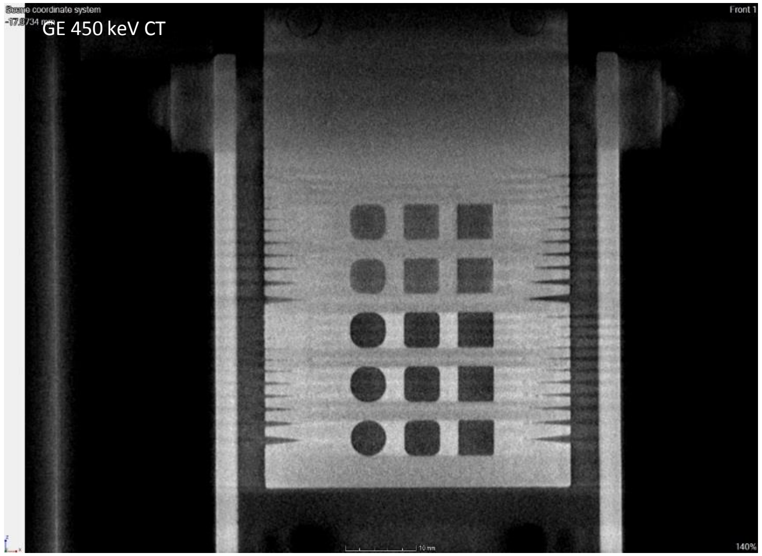

Box 2
Box 1 assembly

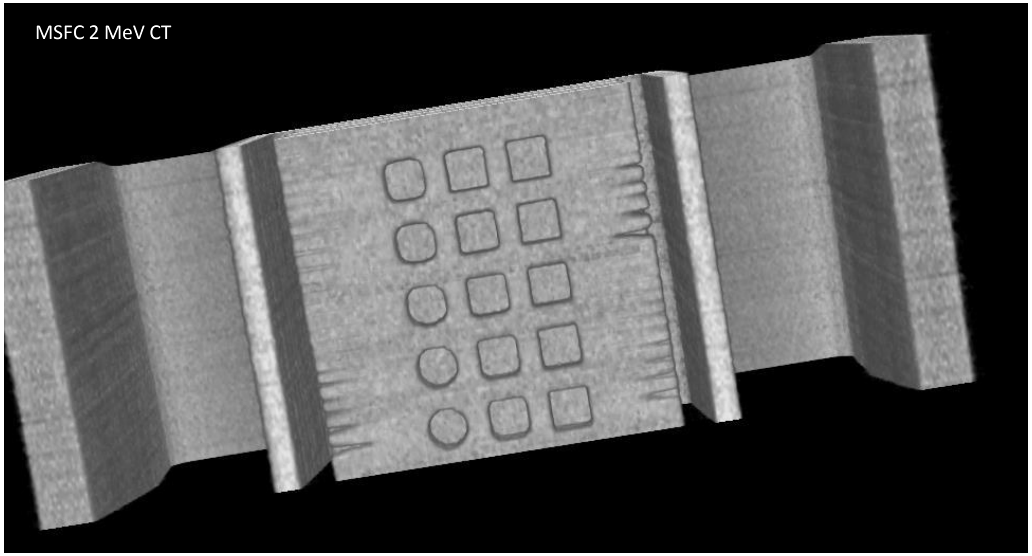
CT OF MODULAR REFERENCE STANDARD



Close-up of features



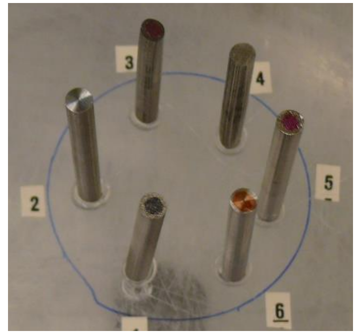




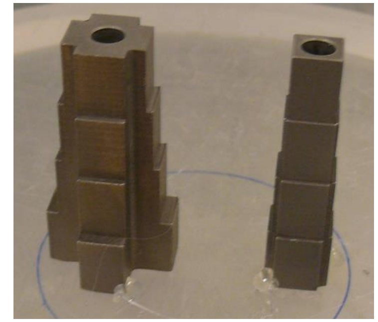
CIRCULAR MODULAR REFERENCE STANDARD (CT DIMENSIONAL ANALYSIS)

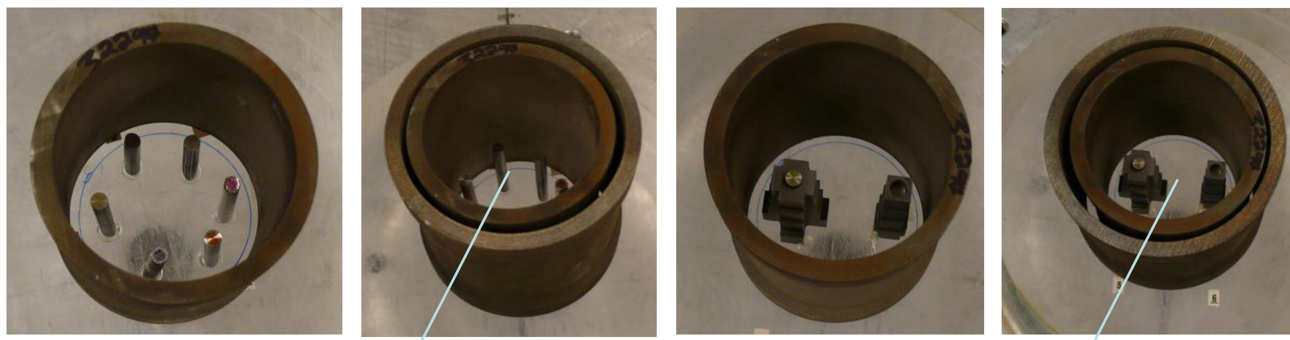
Cylinder 1: 2” diameter x 1/8” wall
Cylinder 2: 3” diameter x 1/8” wall
Cylinder 3: 4” diameter x 1/8” wall

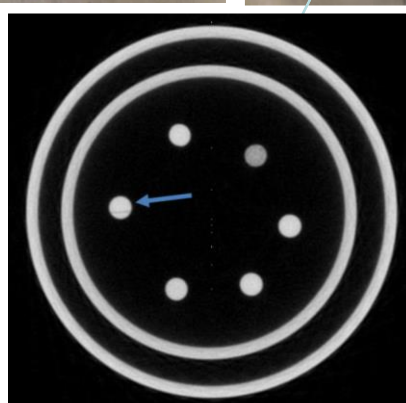
Cylindrical Inserts



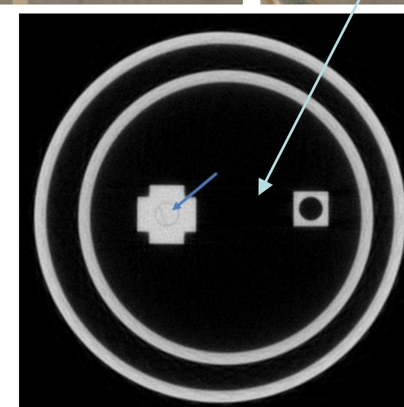
Prisms







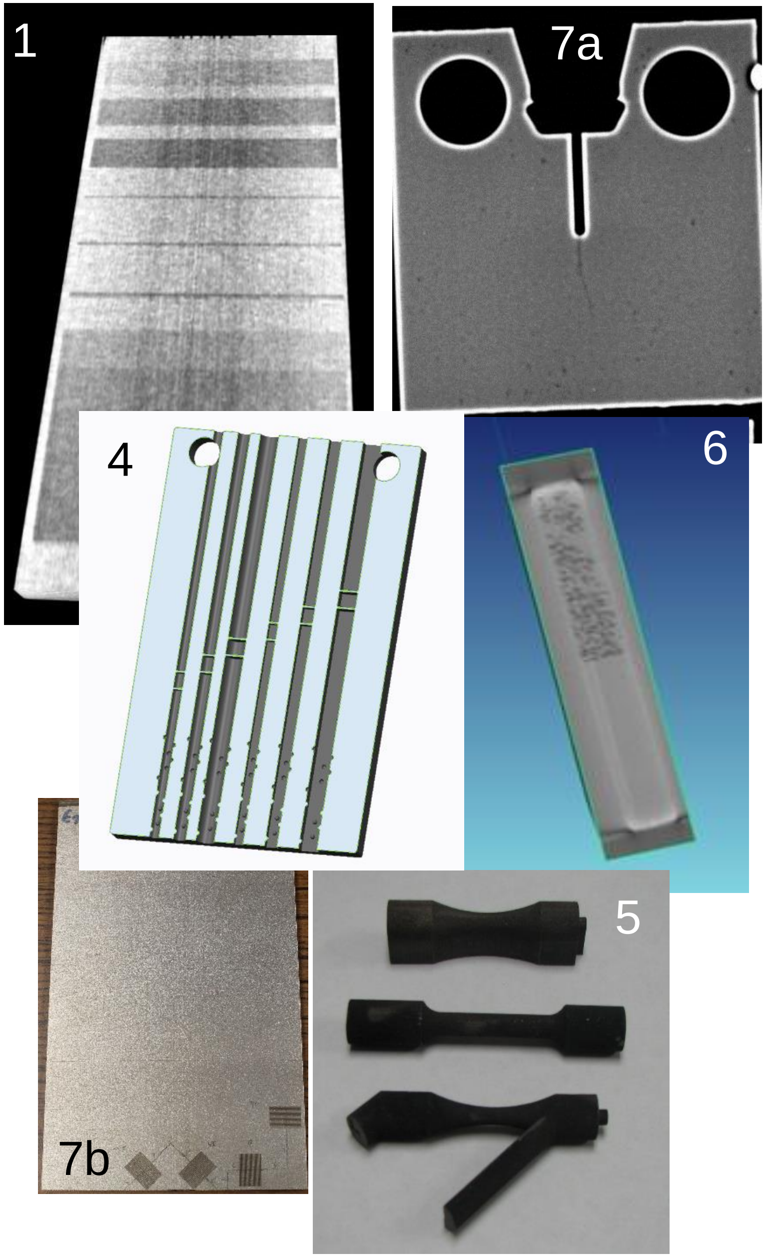
2 MeV CT image



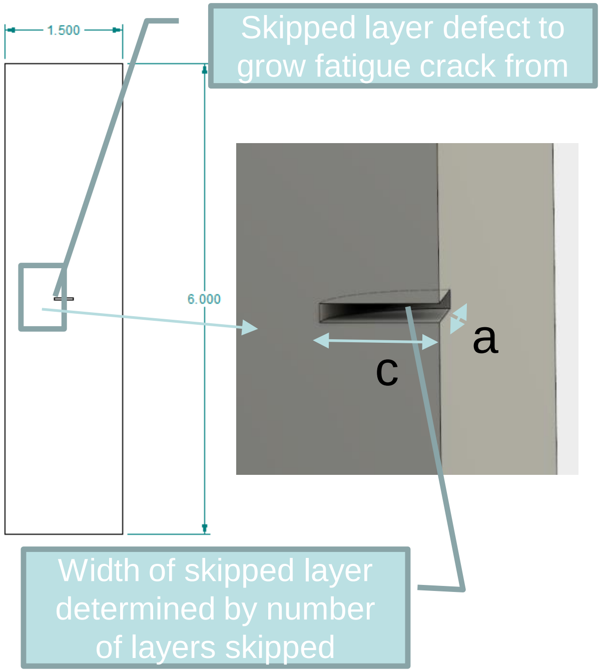
2 MeV CT image

DEFECT CREATION EFFORTS

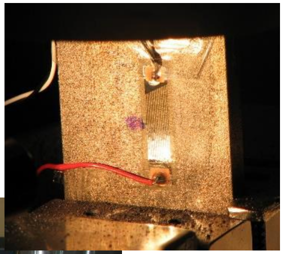
1. **Trapped powder defects**
   - ✓ 4 blocks built (2 stress relief only/2 standard heat treat)
   - ✓ 1” x 8” cross-section box with internal cavities
   - ✓ Powder removed from 2 samples
2. **Machine restart defects**
   - ✓ Effects of a machine shut down
3. **Short feed defects**
   - ✓ Effect of powder starved build area
4. **Channel defects**
   - ✓ Blocked channels (trapped powder)
   - ✓ Improperly formed interior walls
5. **Contamination (soot) defects**
   - ✓ Improper ventilation during manufacture
6. **Skipped-layer defects**
   - ✓ Effects of a region skipped by the laser or low laser power
7. **Crack type defects**
   - a) **Compact tension specimens**
     - ✓ Built in notch
     - ✓ Fatigue cracked
     - ✓ 2 sizes => Approximately 1” and 5” square
     - ✓ 3 thicknesses and 3 build orientations
   - b) **POD samples**
     - ✓ Fatigue loading of skip layer defects to open up a crack
     - ✓ Laser cut simulations

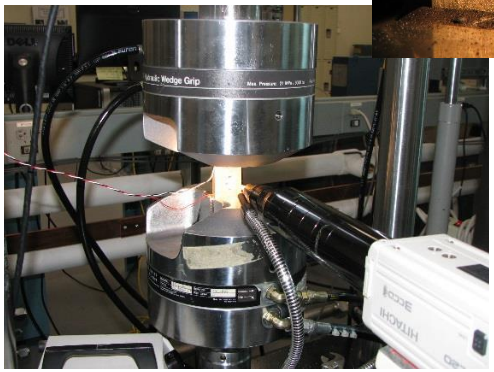


SKIPPED LAYER STARTER NOTCH METHOD



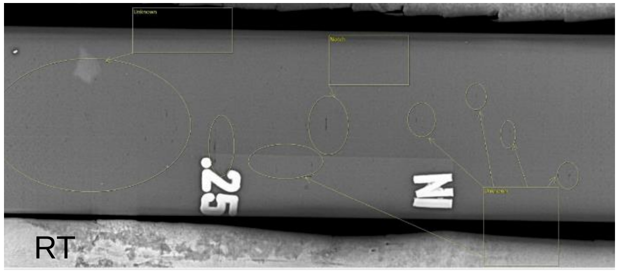
Crack gage used to assess length as crack being formed



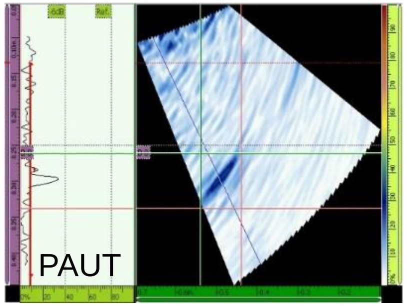


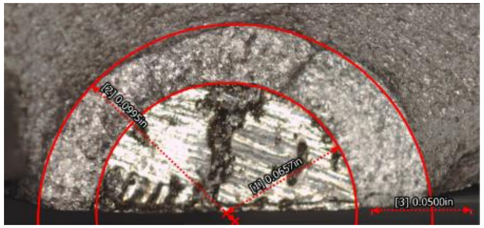
Fatigue loading to create cracks

a (depth)	2c (length)	Width	Location
0.030”	0.060”	0.006”	Surface
0.030”	0.060”	0.011”	Surface
0.030”	0.060”	0.011 “	Embedded
0.050”	0.100”	0.006”	Surface
0.050”	0.100”	0.011”	Surface
0.050”	0.100”	0.011”	Embedded

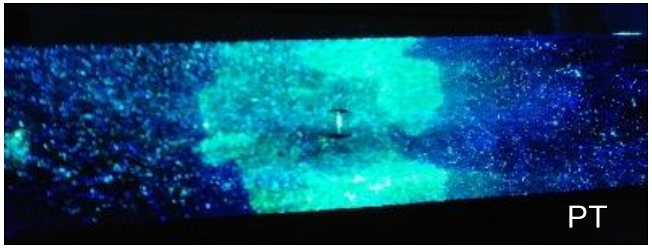


Sample NDE results



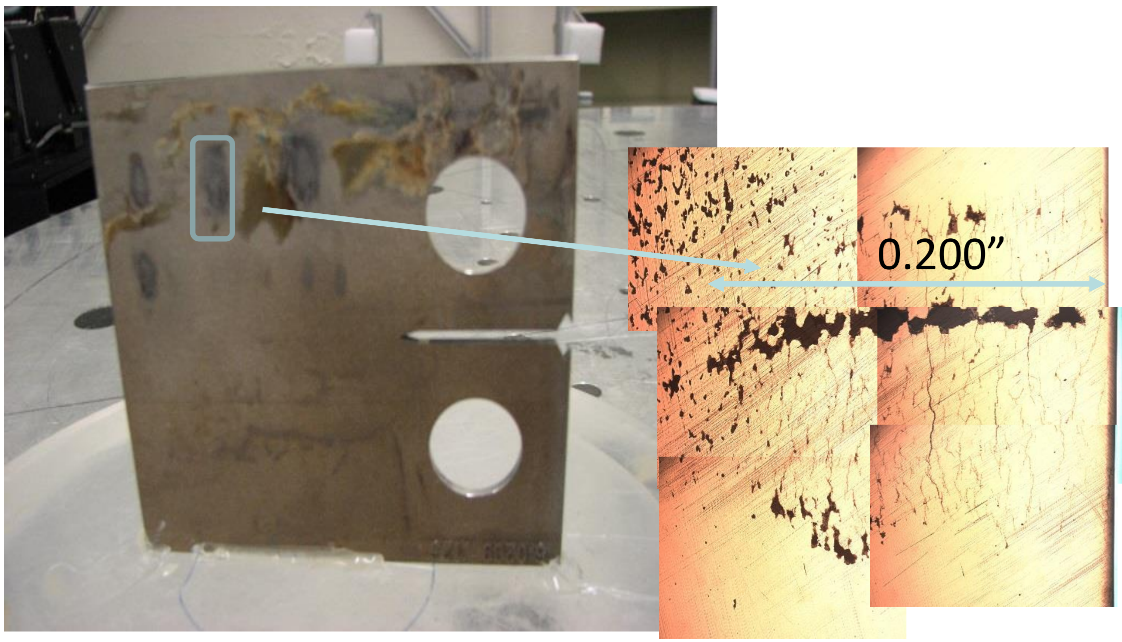


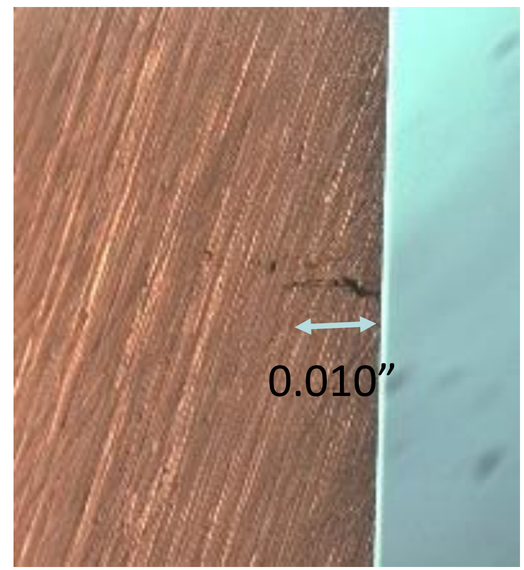
Fracture surface showing extent of skipped layer starter defect and fatigue cracking



LASER/THERMAL METHOD

- TrueFlaw; Finland
- Attempted to put cracks in an AM Inconel 718 sample
- Most of the crack regions showed no cracks or just fine lateral cracking.
- A large area around the "crack" with fine lateral cracks branching off the main feature.



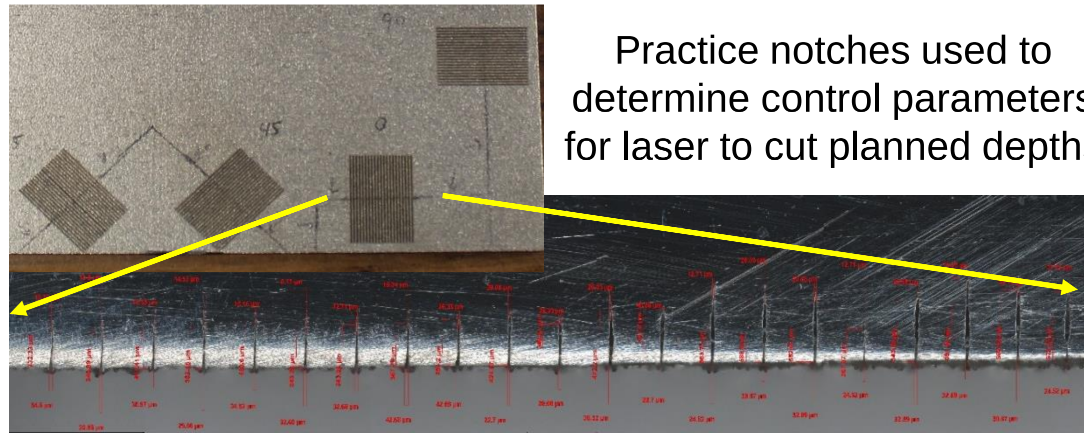


LASER MACHINING METHOD

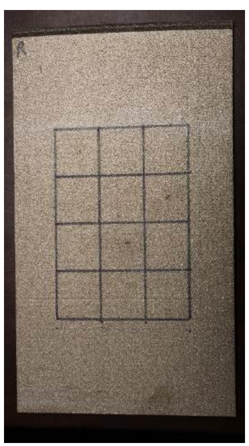
- Universal Technology Corporation
- 5” wide x 10” tall x 0.25” thick as-built Inconel 718 samples POD architecture => 80 notches => 15 (5” x 8” x 0.25”) panels => 4 depths (0.010”, 0.020”, 0.030”, 0.040”), 4 orientations (0, 45, -45, 90) and 5 lengths (0.025”, 0.050”, 0.075”, 0.100”, 0.125”)
- POD study for penetrant, eddy current, radiography, ultrasonics and computed tomography

Practice panel

Laser cut crack

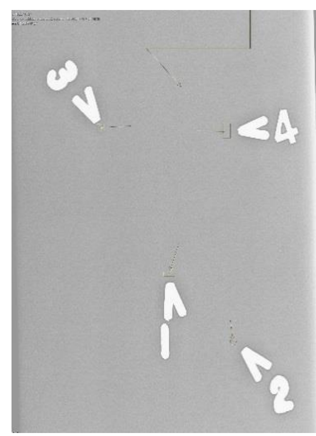


Practice notches used to determine control parameters for laser to cut planned depths

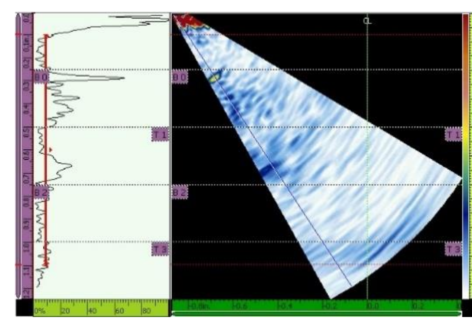


Typical POD panel

Penetrant



Radiography



Ultrasonic

Sample initial NDE results

PARTING THOUGHTS

Conventional NDE

- The jury is still out on the ability of conventional NDE to inspect “accessible regions” of AM hardware, much more work needs to be done in this area.
- For inaccessible regions the NDE community still needs to look at the practical limitations of CT.
- Much more work needs to be done to understand the damage tolerance of AM components and the effects-of-defects.
- CT dimensional metrology needs a lot of attention.
- AM is a rapidly evolving technology. Hence, NDE is trying to hit a moving target. When a solution is found for a problem, manufacturing may have moved on so that the solution no longer applies.

In-situ NDE

- Can track the “process” as an AM structure is built
- What does that ultimately tell us about the final build?
- How will we certify in-situ NDE?
- What would a probability of detection study look like?

Ultimately, just because it can be built, should it?

We need to help the AM industry not forget about design for inspectability.

Q&A

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