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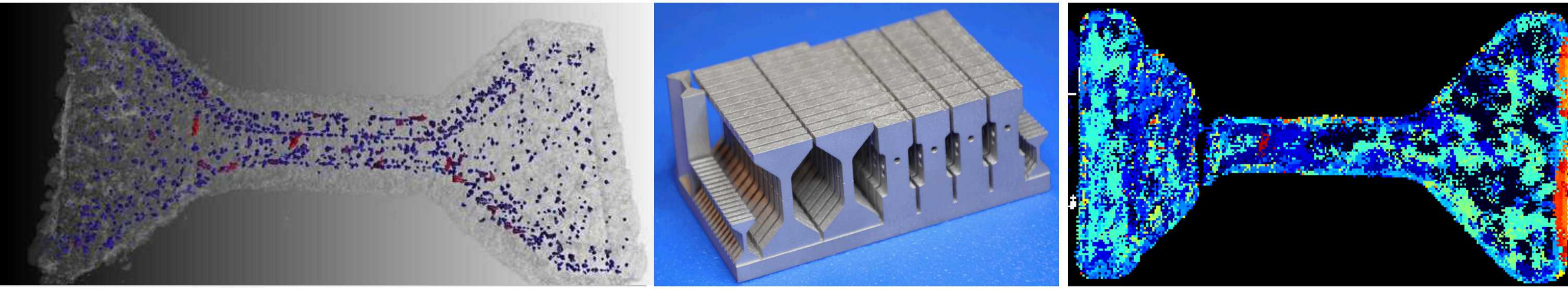

Characterization and Nondestructive Inspection of Additively Manufactured Materials

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Additive Manufacturing (AM) Overview

- Fast build time and low production cost
- Ideal for small production quantities
- Topology optimization
  - Build multiple components into one part within the same build
  - Define the build path to optimize material properties
- Create and build designs that are impossible to manufacture with conventional machining techniques
- Variety of additive manufacturing methods available
  - Powder bed fusion
  - Vat polymerization
  - Extrusion-based AM
  - Material jetting
  - Binder jetting
  - Material lamination
  - Directed energy deposition

Challenges

- Inspection
- Qualification
- Part-to-part variability
- Material characterization
  - Residual stresses
  - Mechanical properties

I. Gibson, D. Rosen, and B. Stucker, *Additive Manufacturing Technologies: 3D Printing, Rapid Prototyping, and Direct Digital Manufacturing*, 2nd ed., Springer, 2015. ISBN 978-1-4939-2112-6.

Powder Bed Additive Manufacturing

Direct Metal Laser Sintering (DMLS) power bed fusion

Introduction

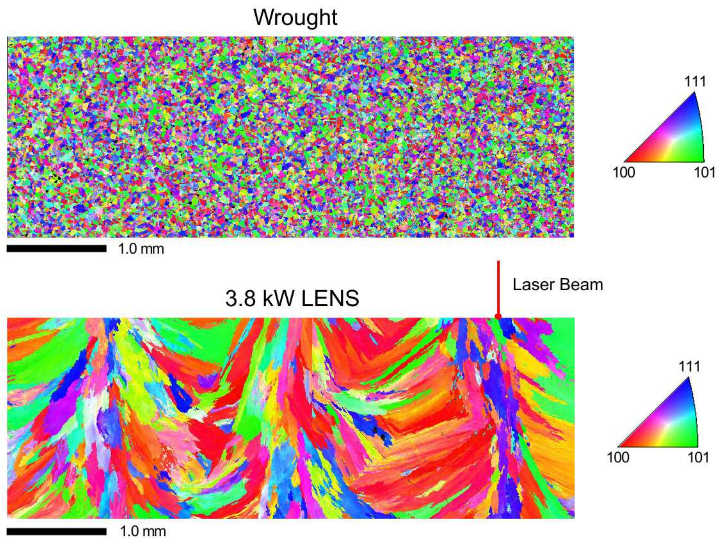
- What aspects of AM materials affect mechanical performance?
  - How do you qualify the powder? Can it be reused?
  - What is the effect of porosity in a sample? What is the allowable limit?
- Two materials of focus
  - AlSi10Mg
  - 304L Stainless Steel
- Part-to-part variances and qualification
  - Strength
  - Ductility
  - Toughness
- Which qualification tests are relevant?
  - Density versus Charpy (direct dynamic cracking)
  - Tension (strength and ductility)
  - Fractographic analysis
- Which NDE/NDI technique(s) should be used for research and qualification?

Identifying Acceptable Metrics for AM Parts

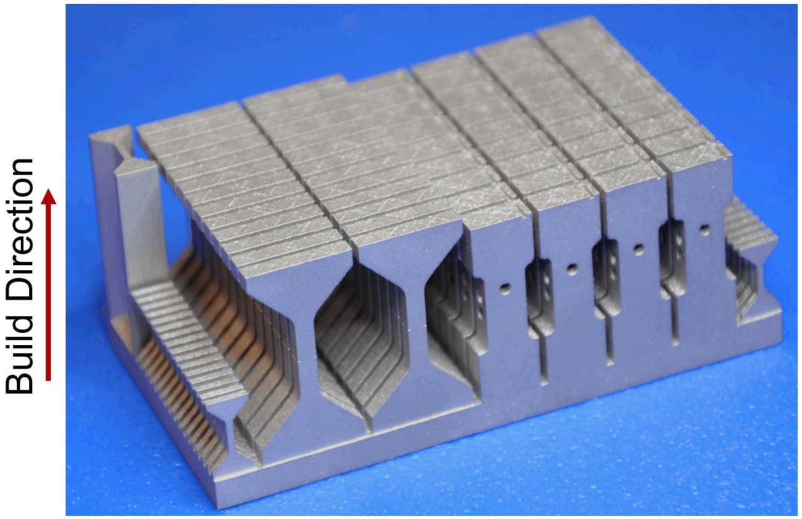
- **<u>Goal:</u>** Need to gain a better understanding of the microstructure of AM materials and how it affects the material properties
- Perform a suite of mechanical and diagnostic tests
  - Tensile and torsional tests
  - Charpy impact tests
  - Computed tomography
  - Ultrasound inspection
  - Fractographic analysis

Identify which mechanical tests demonstrate material's ability to meet performance requirements (tensile and torsional tests; Charpy impact tests)

Identify which diagnostic tools characterize the microstructure (computed tomography; ultrasound inspection; fractographic analysis)



Comparison of microstructure (grain structure and grain orientation) of wrought and AM 304L



AM Parts with Witness Samples for Mechanical Characterization

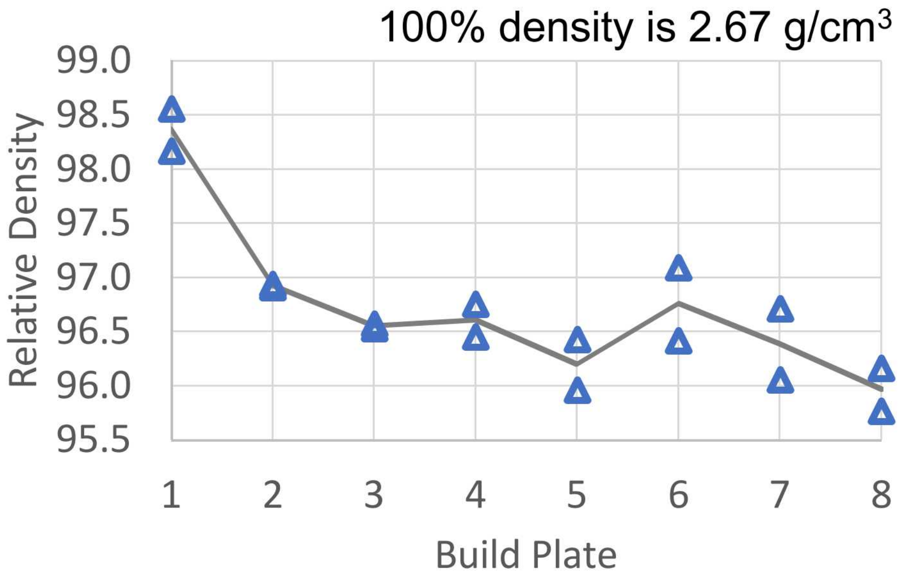
Sandia National Laboratories

Case Study

AlSi10Mg Tensile Bar with Flat Bottom Holes

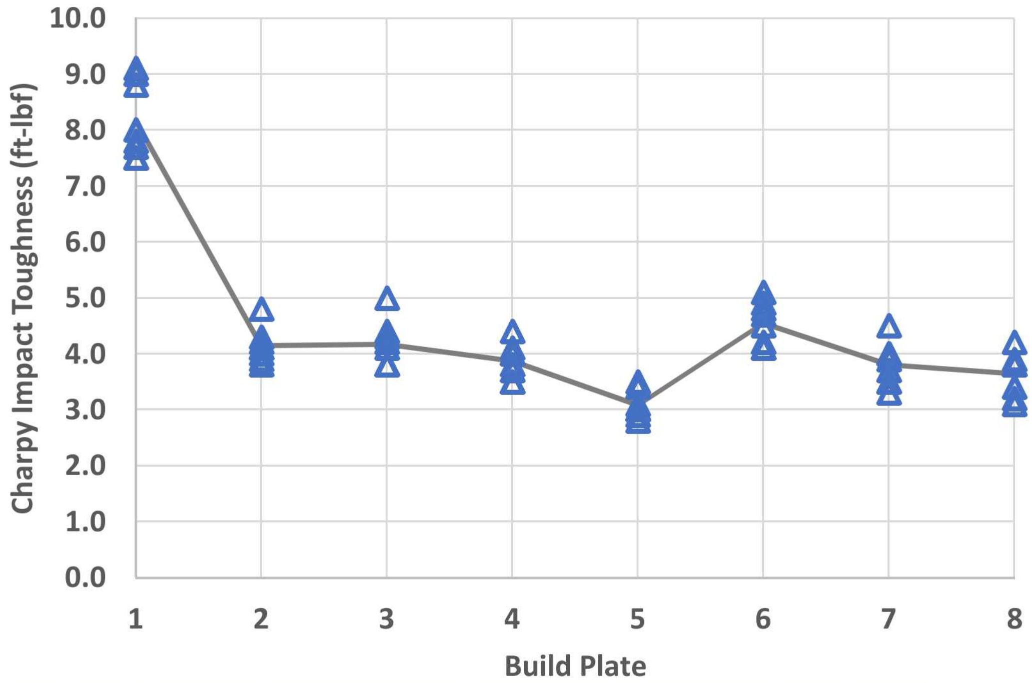
Effects of Reusing Powder

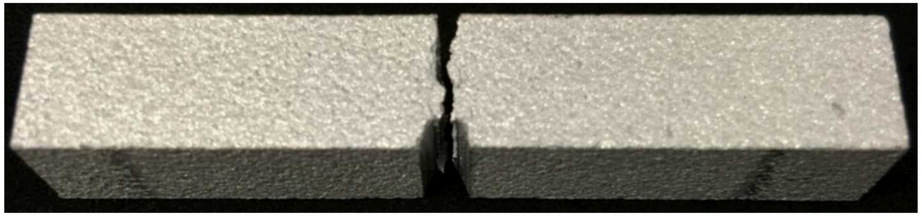
Build	Powder condition
1	**Fresh**
2	Reused **1 time**
3	Reused **2 times**
4	Reused **3 times**
5	Reused **4 times**
6	**Fresh**
7	Reused **1 time**
8	Reused **2 times**

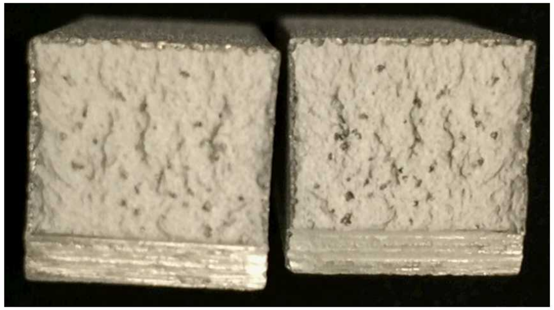


- Reusing the powder leads to decreased relative density
- The parts are made using approximately 10% of the AlSi10Mg powder used in the build
- If the relative density decreases with reused powder, how does this affect the mechanical properties of the final part?

Charpy Impact Test Results

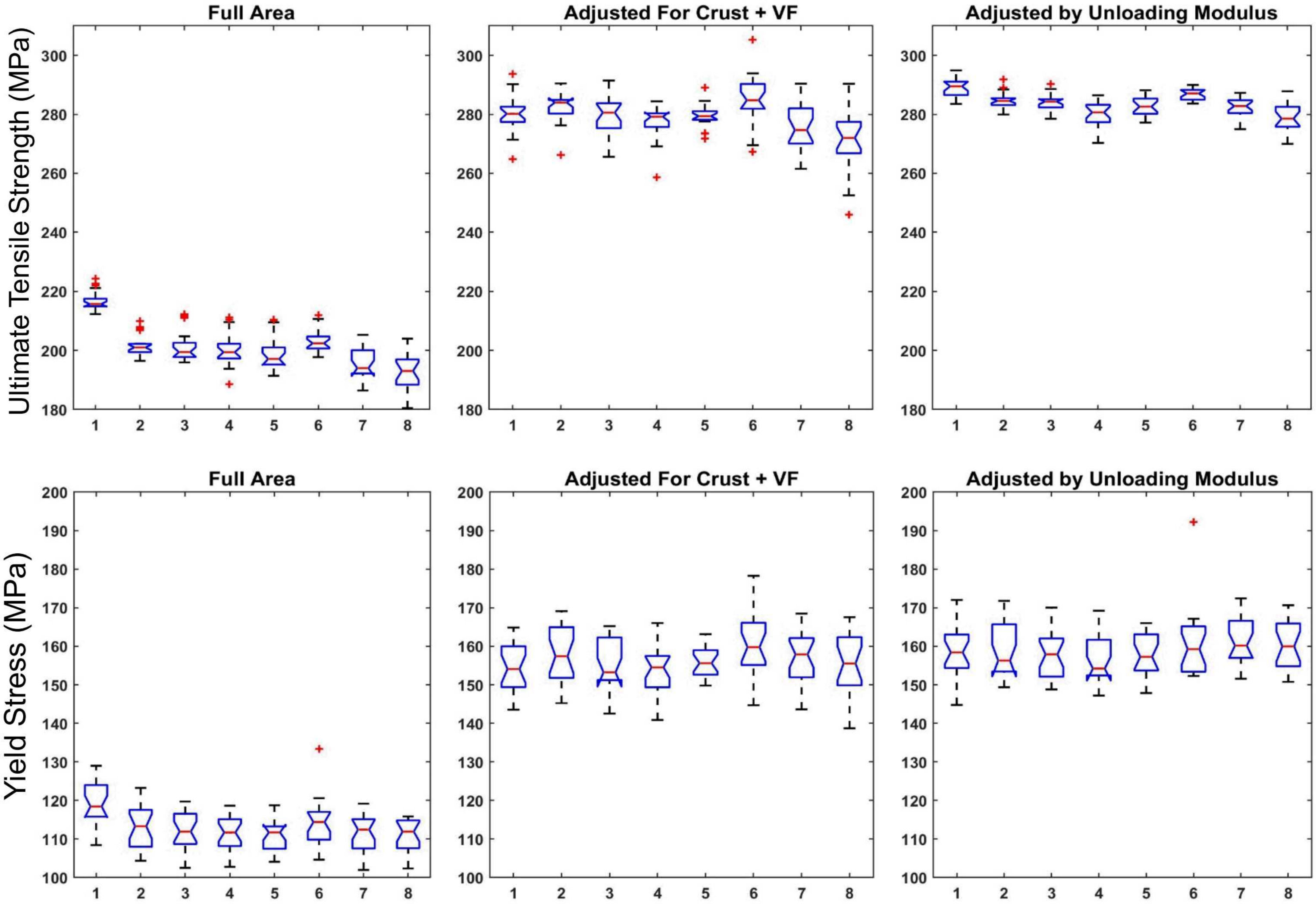






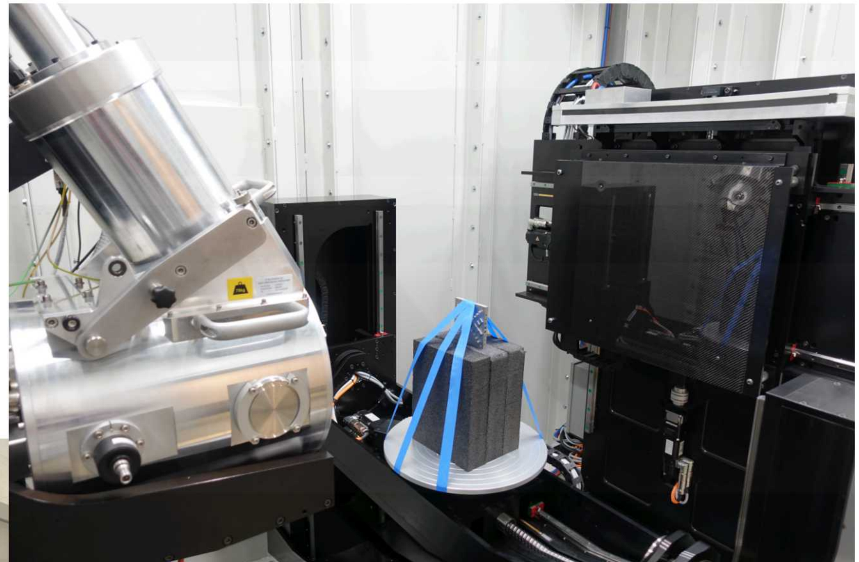
- Rapid test and analysis
- Fracture toughness is approximately 15 MPa√m
- Known failure area (notched section)
- Good for quality control because sample is affected by AM build parameters

Surface and Porosity effects on ultimate tensile strength



- “Inherent” Tensile strength is ~280 MPa instead of ~200 MPa.
- “Inherent” Yield stress is ~190 MPa instead of ~120 MPa.

Baseline CT Equipment Dual Head



225kV Rotating Anode Tube

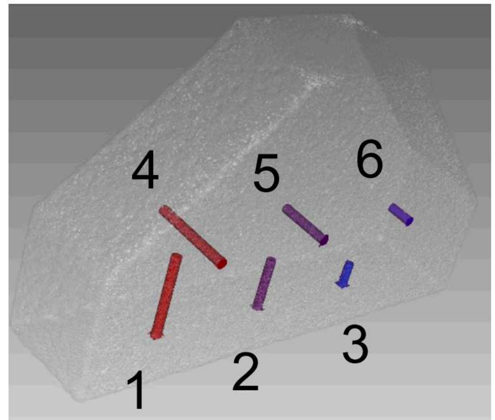
- 225kV 450W Rotating Target Micro-Focus X-Ray source
- Minimum spot size 10 microns

450kV kV High (Rotating target)

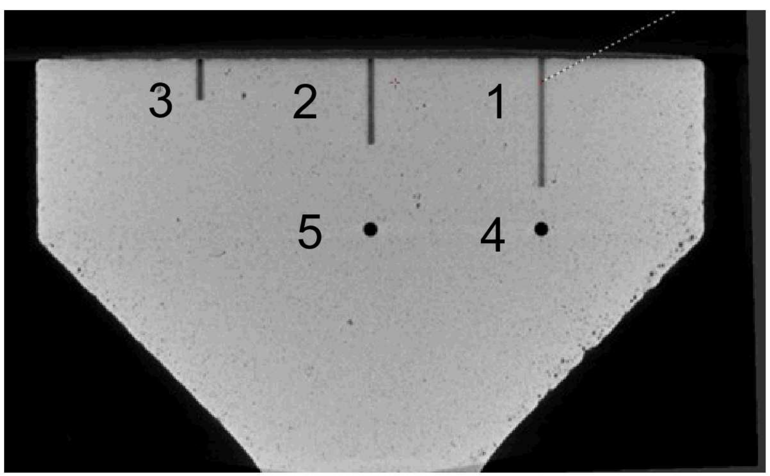
- 450kV/450W High power
- X-Ray spot size < 80 microns up to 200W

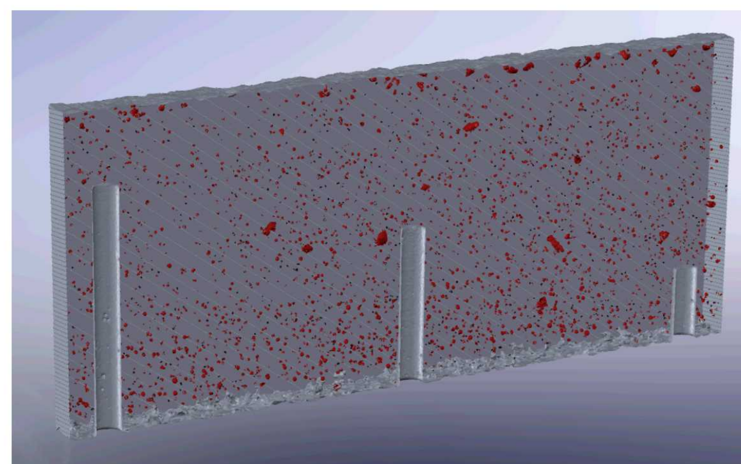
Identifying the Flat Bottom Holes and Void Assessment

- While analyzing the CT data, each of the six holes can be identified and their diameter measured
- As seen in the lower right image, a porosity analysis can also be performed on the CT data to highlight the sample's porosity content (seen in red)

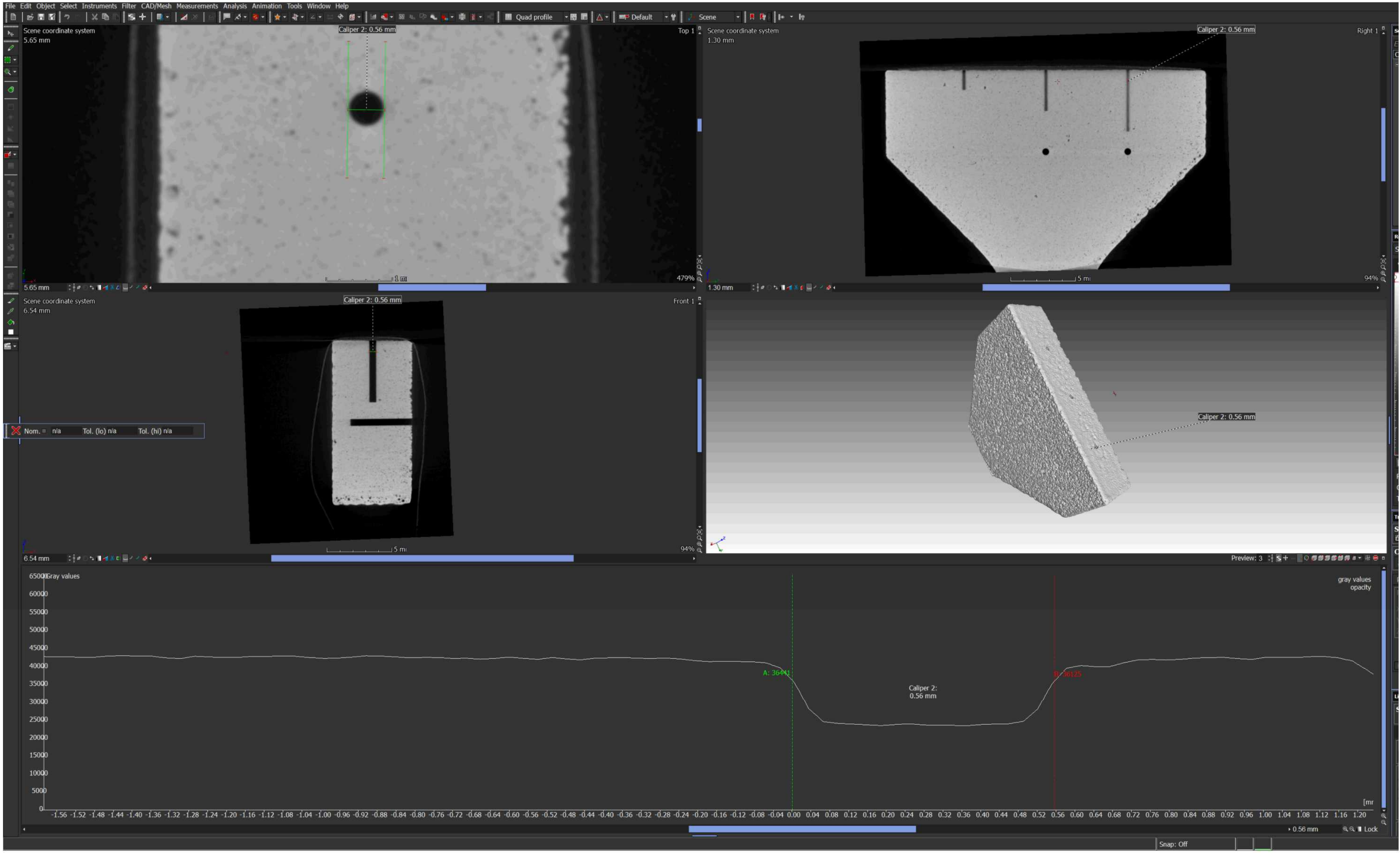


Drilled Hole Measurements		
Hole #	Diameter (mm)	Hole Depth (mm)
1	0.51	4.79
2	0.52	3.21
3	0.52	1.56
4	0.52	4.78
5	0.52	3.18
6	0.53	1.52



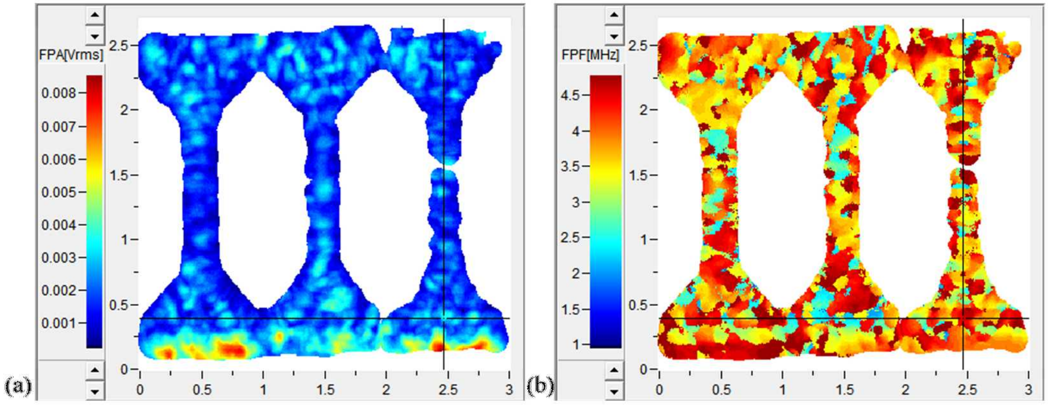


Measuring the Flat Bottom Holes with CT

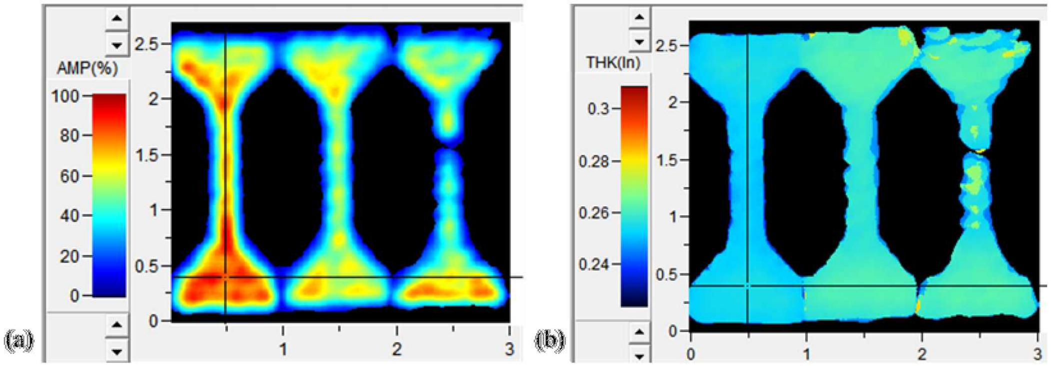


Ultrasound Inspection Overview

- Pulse echo immersion ultrasound inspection of AM tensile bars
- Ultrasound analysis of the backwall signal can detect differences between the types of powders usec (fresh or recycled)
  - Left bar – fresh powder
  - Center bar – four times recycled
  - Right bar – two times reused powder
- The right-most tensile bar has a fracture in it as seen in the C-scan
- **If results are able to identify differences in powder and powder is related to porosity content, ther is the potential to calibrate the inspection to identify porosity.**

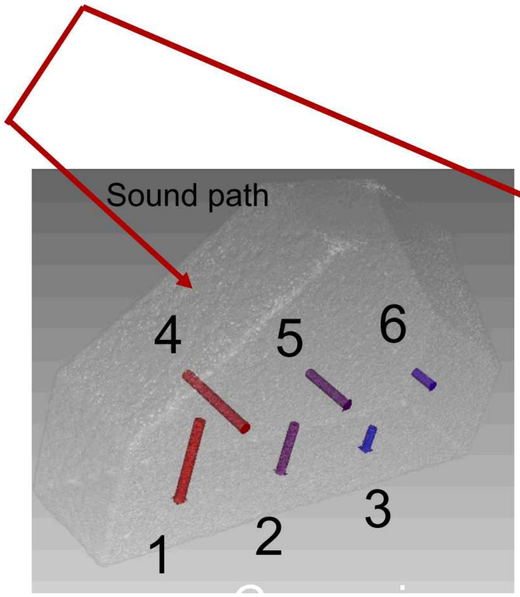


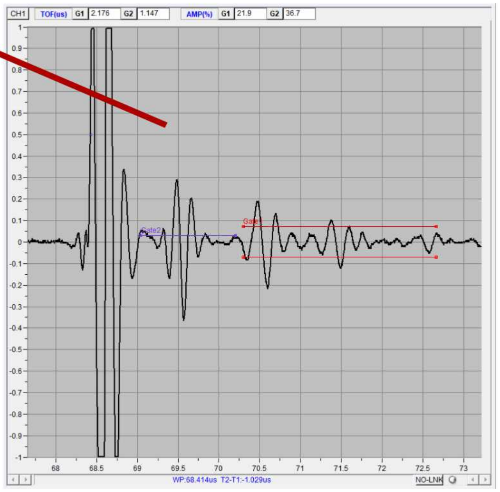
(a) Amplitude peak (volts) and (b) Frequency peak in the ultrasound C-scan data.



Ultrasound monitoring (a) amplitude and (b) time of flight

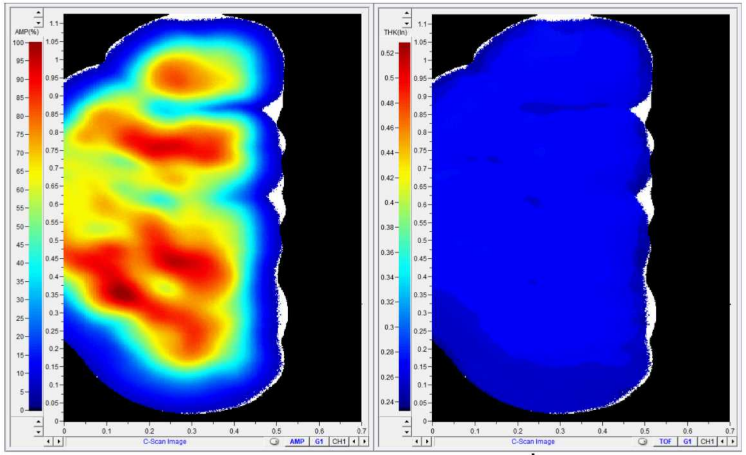
Identifying Drilled Holes at 10 MHz



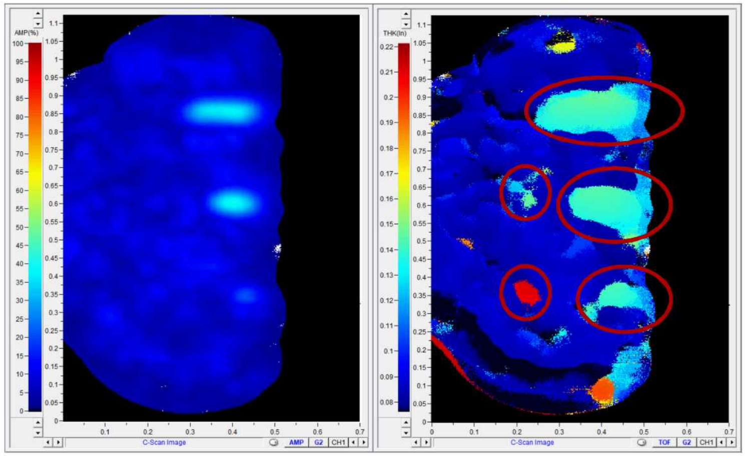


10Mhz; F.L. = 7.62 cm
On the front surface.

- Identified holes 1, 2, 3, 5, and 6
- Hole 4, which has the least distance to the top surface, was not identified

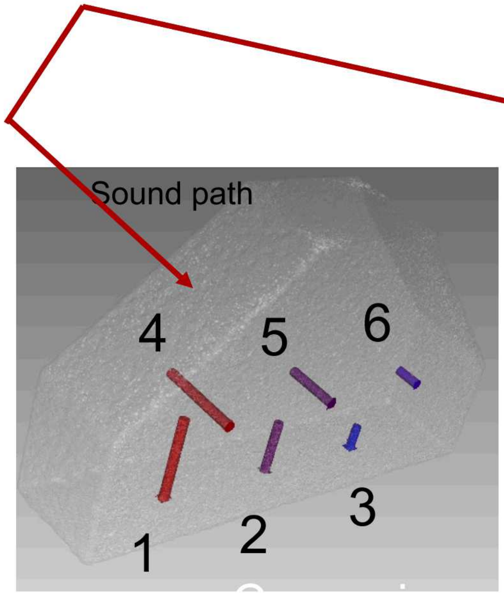


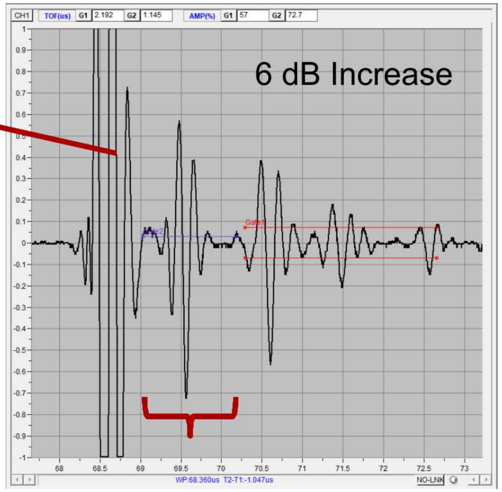
Gate 1 – Backwall and 2nd Reflection

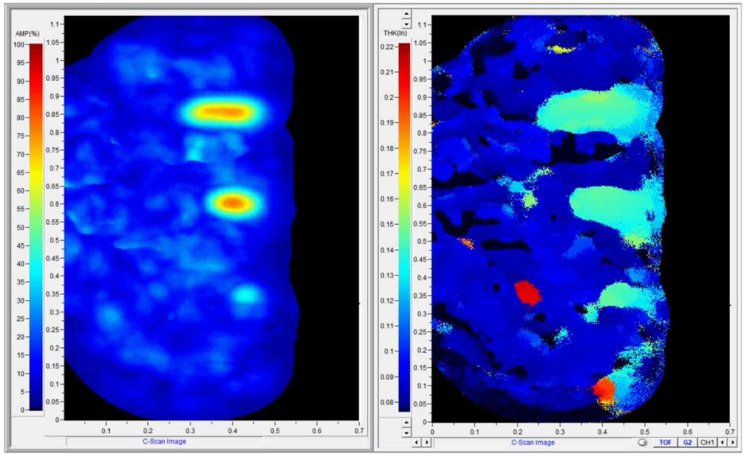


Gate 2 – Thickness of Sample

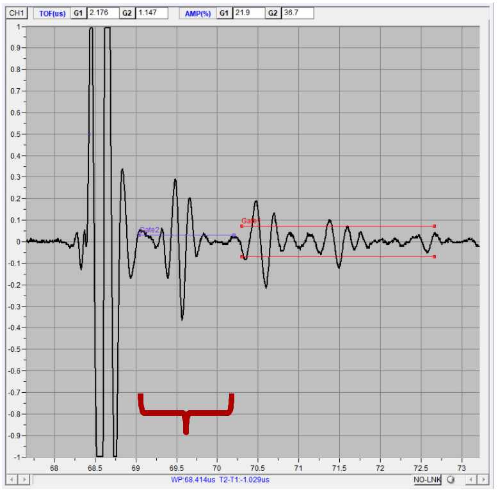
Drilled Hole Assessment at 10 MHz (Gate 2)

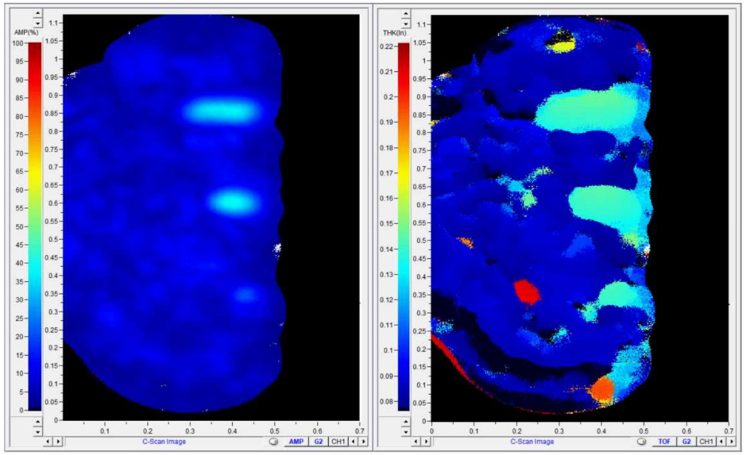






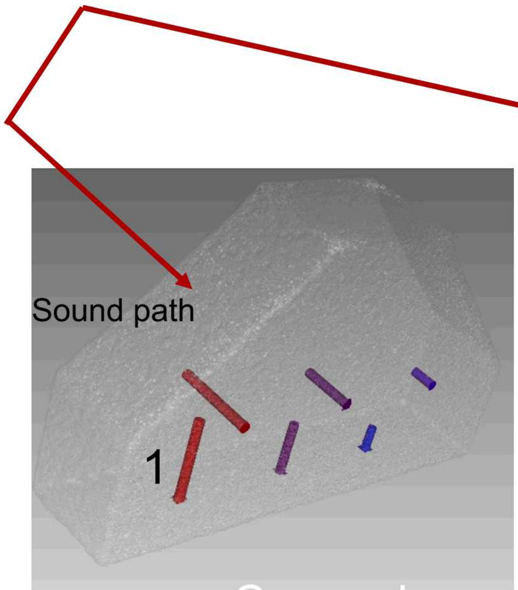
10Mhz; F.L. = 7.62 cm
On the front surface.

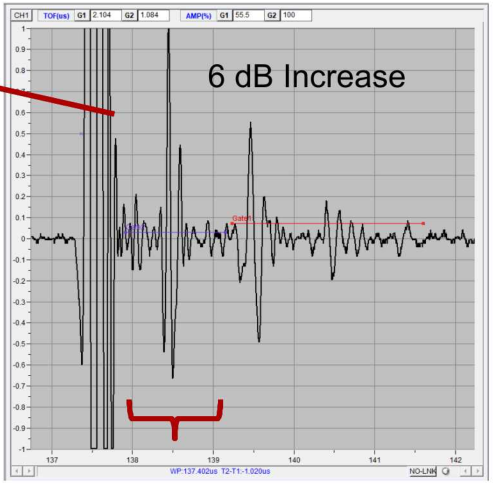


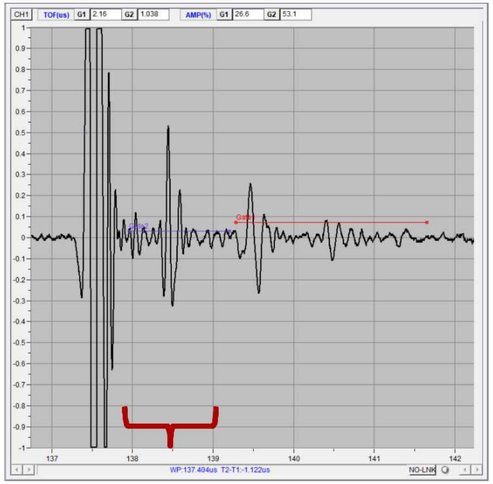


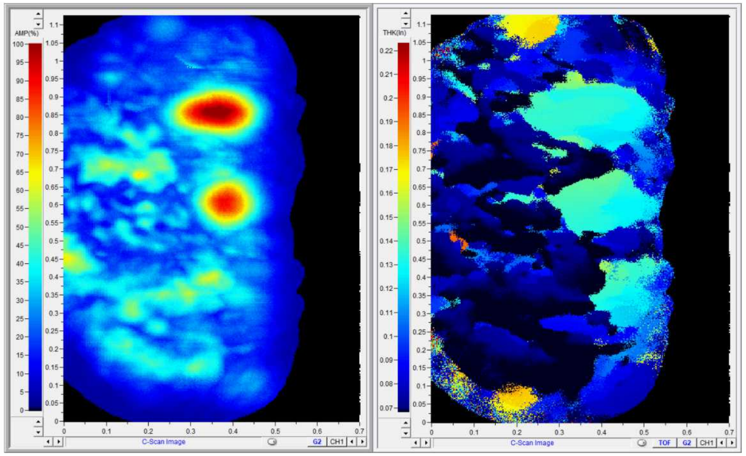
As gain is changed the signal to noise increases. This makes the detection of the flat bottom holes difficult. The side drilled holes are easier to find.

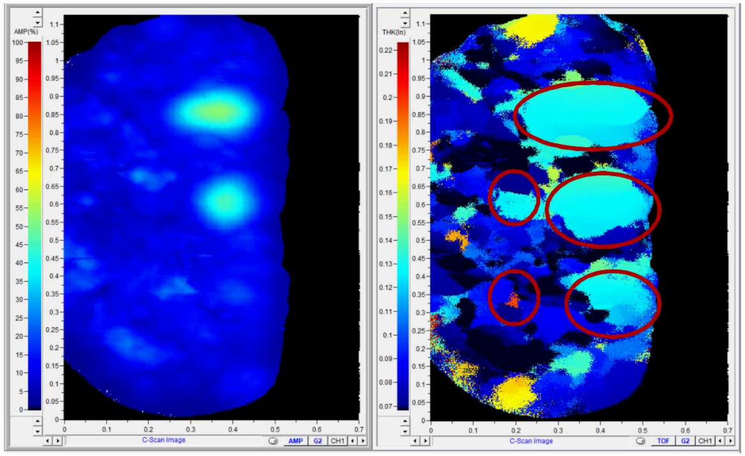
Drilled Hole Assessment at 15 MHz (Gate 2)











15Mhz; F.L. = 12.7 cm
On the front surface.

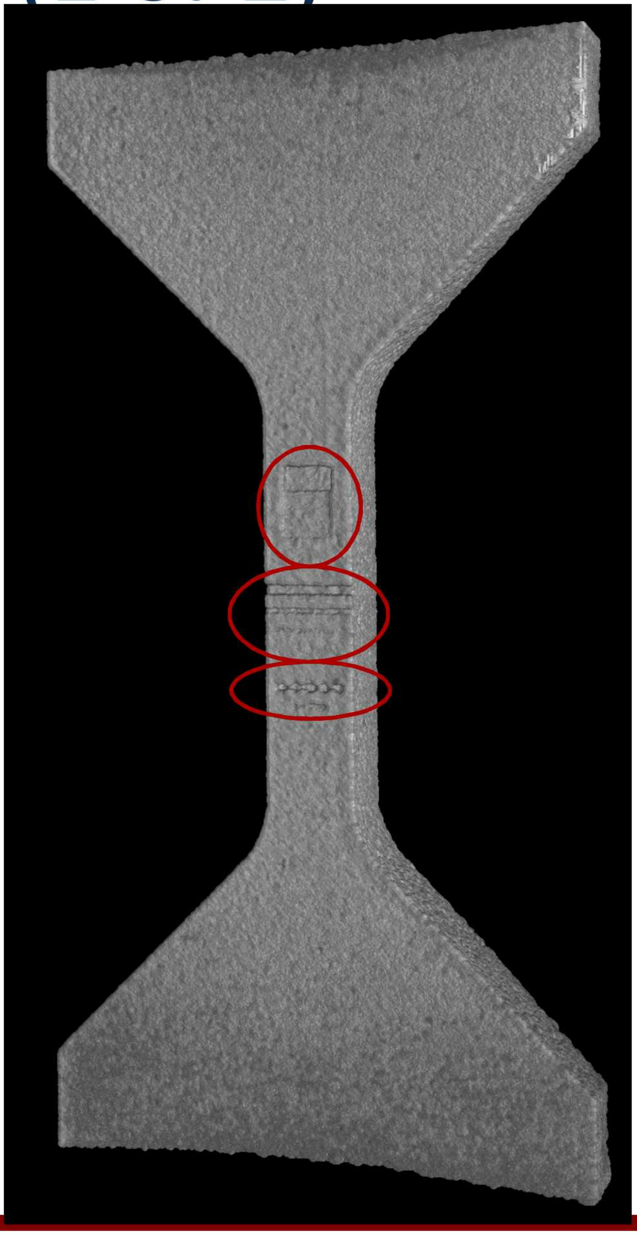
As gain is changed the signal to noise increases. This makes the detection of the flat bottom holes difficult. The side drilled holes are easier to find.

Case Study

304L Stainless Steel Tensile Bars

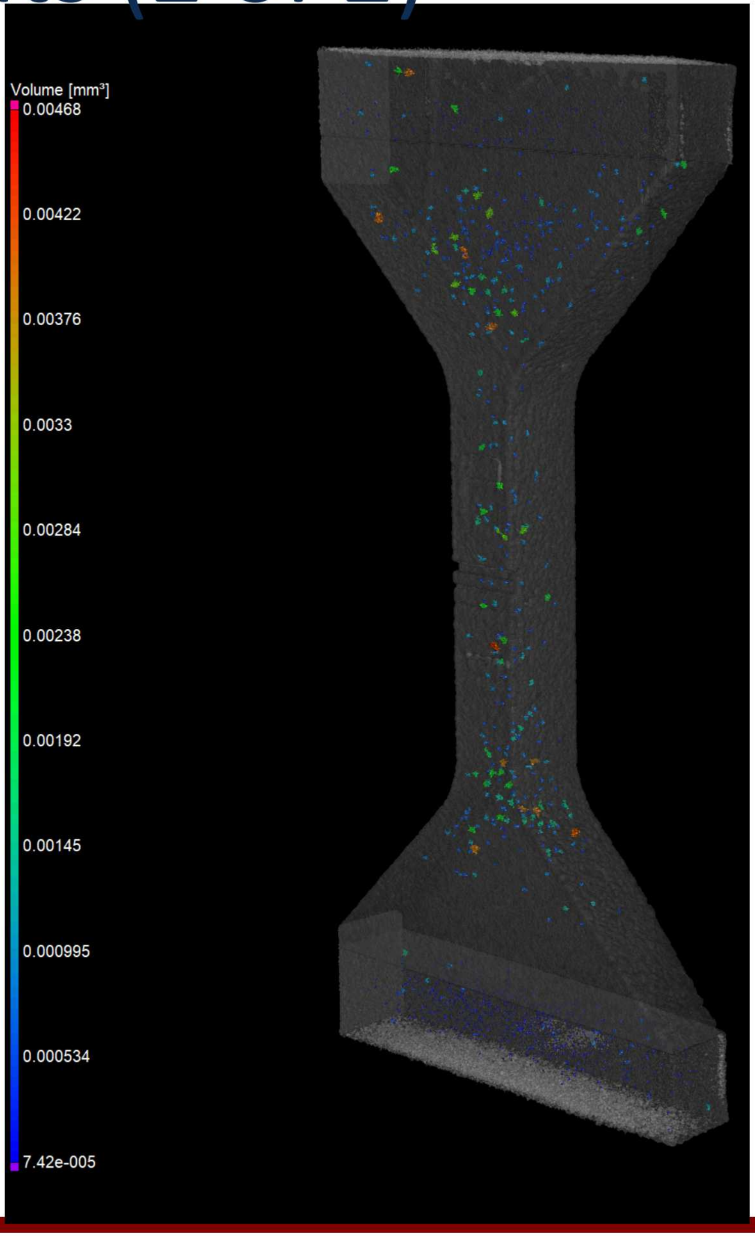
CT Inspection Results (1 of 2)

- The 2.5 mm thick sample contains three distinct types of marks along the gauge length of the tensile bar
  - Five circular marks across the width
  - Three horizontal notches of varying depths
  - A stepped region with three different step depths located above the centerline
- These features can be identified and measured using the CT data



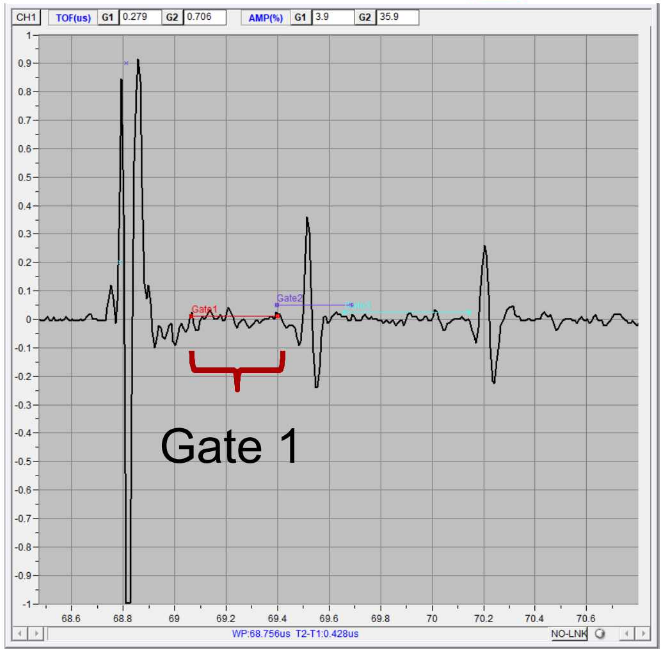
CT Inspection Results (2 of 2)

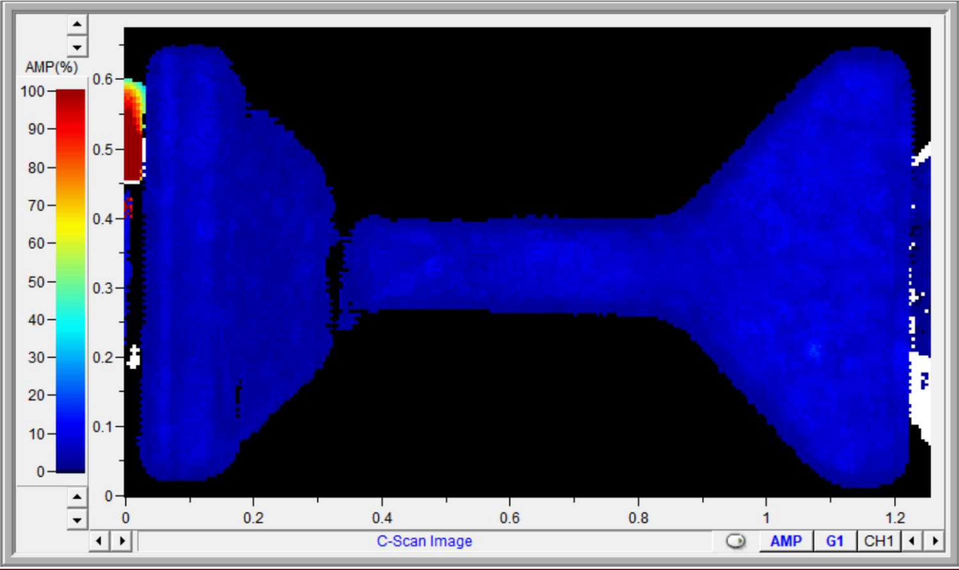
- A porosity analysis was also performed on the CT inspection data and the results are shown at right
- The sample was broken into three regions to increase the computational speed of the porosity analysis
  - Each grip region (rectangular)
  - Remaining central section of the tensile bar
- The larger pores tend to be located near the center of the tensile bar

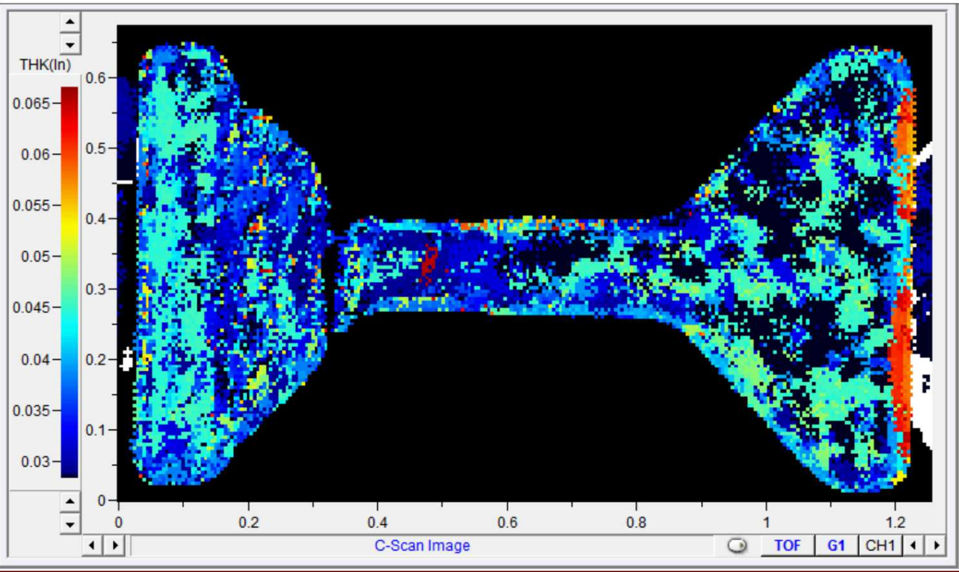


Tensile Bar – 2.5 mm Thick

- Pulse echo immersion ultrasound inspection of AM tensile bars
- 30 MHz spherically focused probe
- Focal length = 7.62 cm (3 in.)
- Gate 1 captures the A-scan corresponding to <u>wave propagation through sample thickness</u>

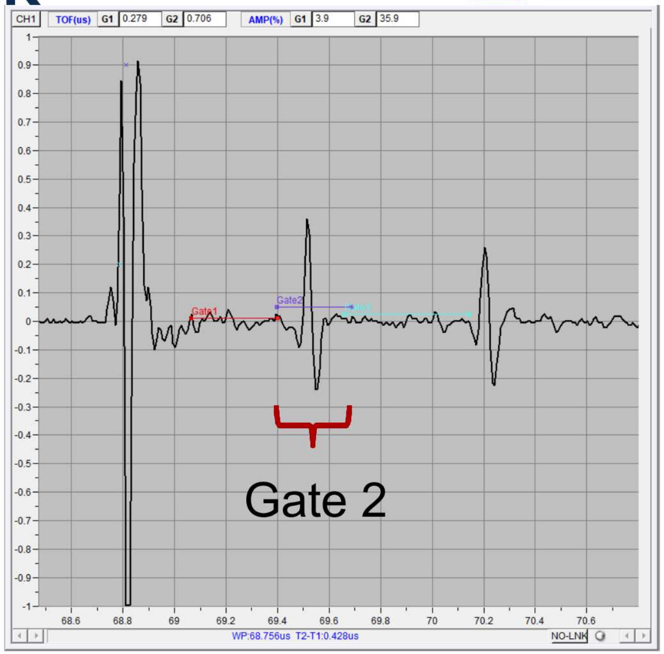


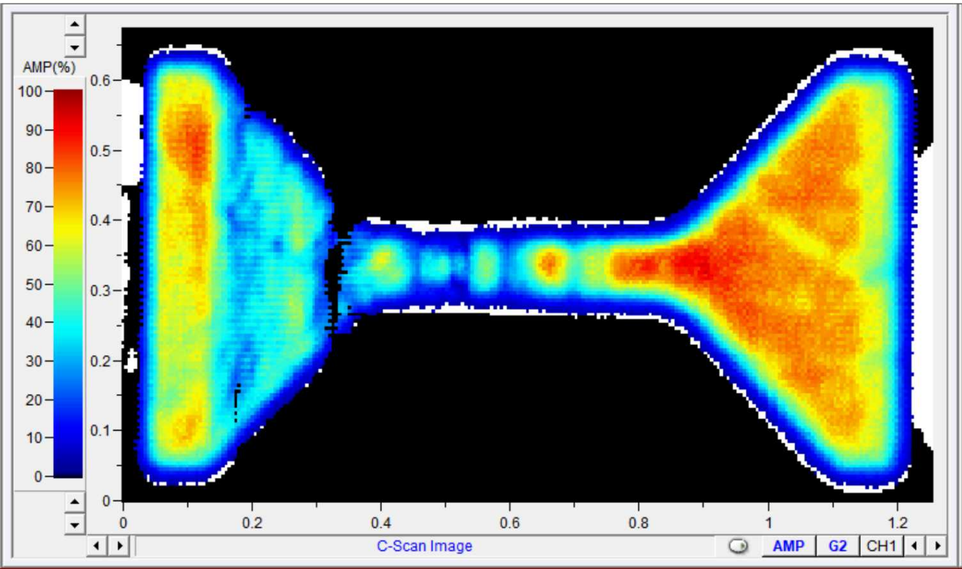


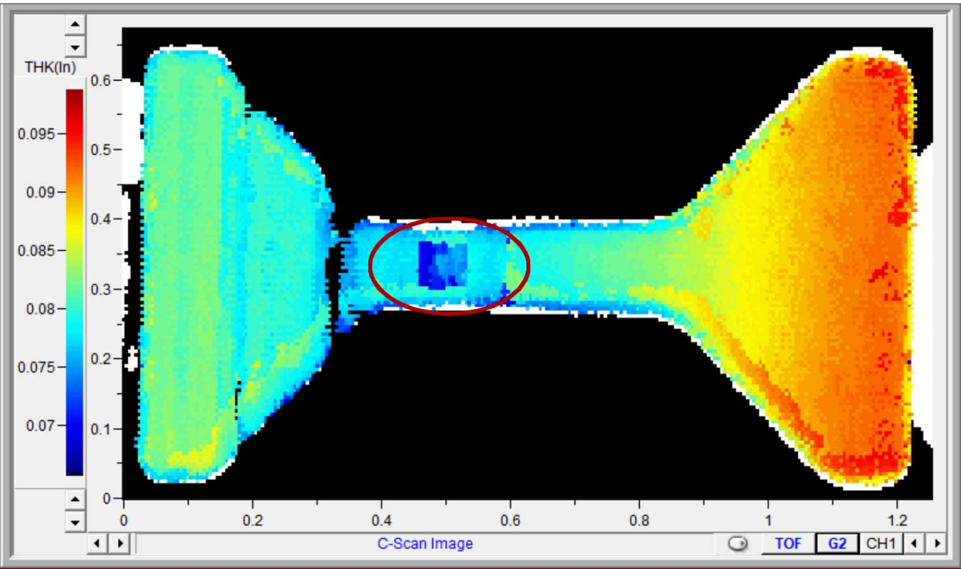


Tensile Bar – 2.5 mm Thick

- Pulse echo immersion ultrasound inspection of AM tensile bars
- 30 MHz spherically focused probe
- Focal length = 7.62 cm (3 in.)
- Gate 2 measures the backwall signal
- Can identify the step feature, but resolving details, such as the depths is difficult

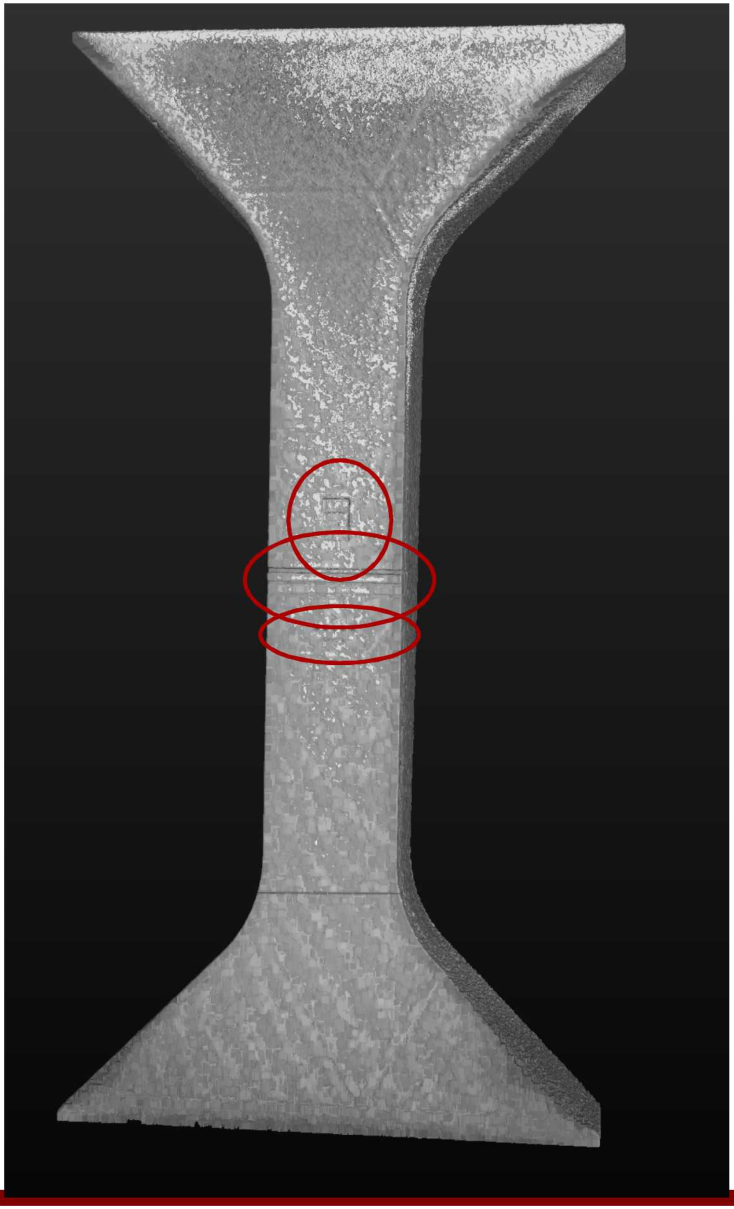






CT Inspection Results (1 of 2)

- The 6.25 mm thick sample contains three distinct types of marks along the gauge length of the tensile bar
  - Five circular marks across the width
  - Three horizontal notches of varying depths
  - A stepped region with three different step depths located above the centerline
- These features can be identified and measured using the CT data

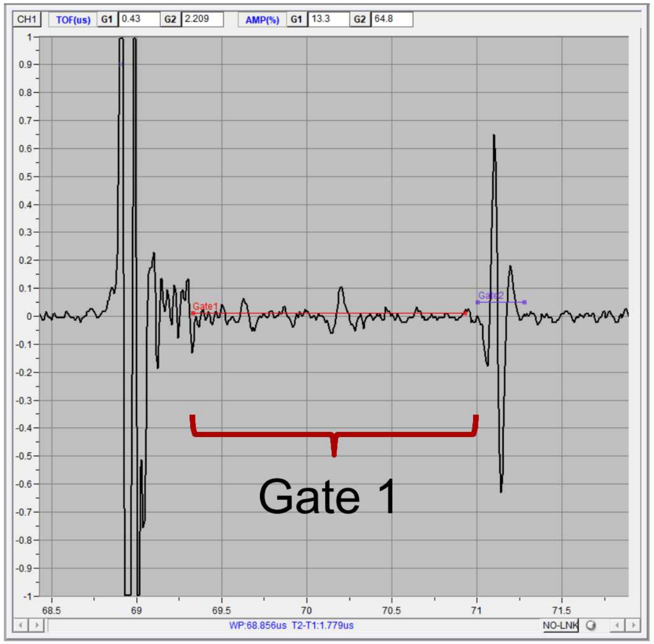


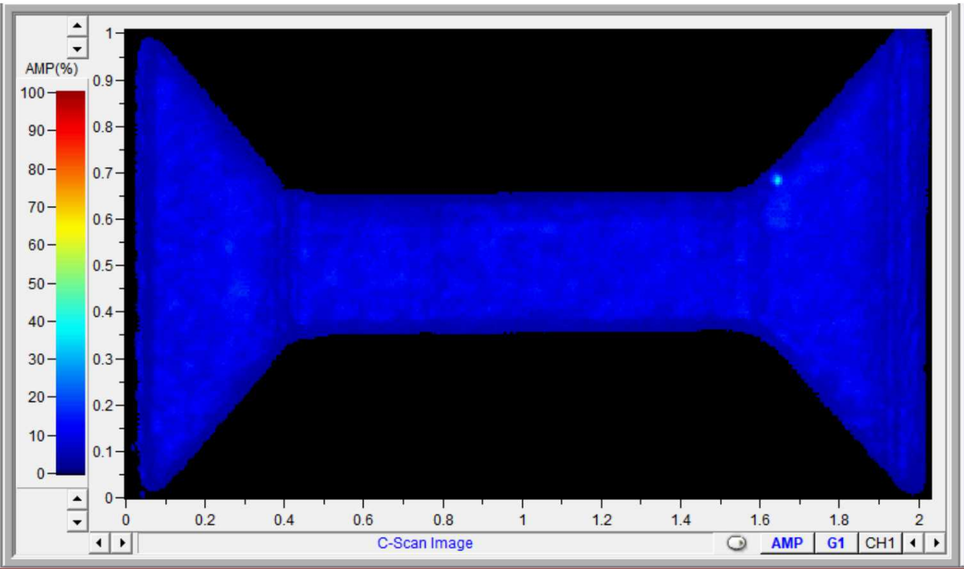
CT Inspection Results (2 of 2)

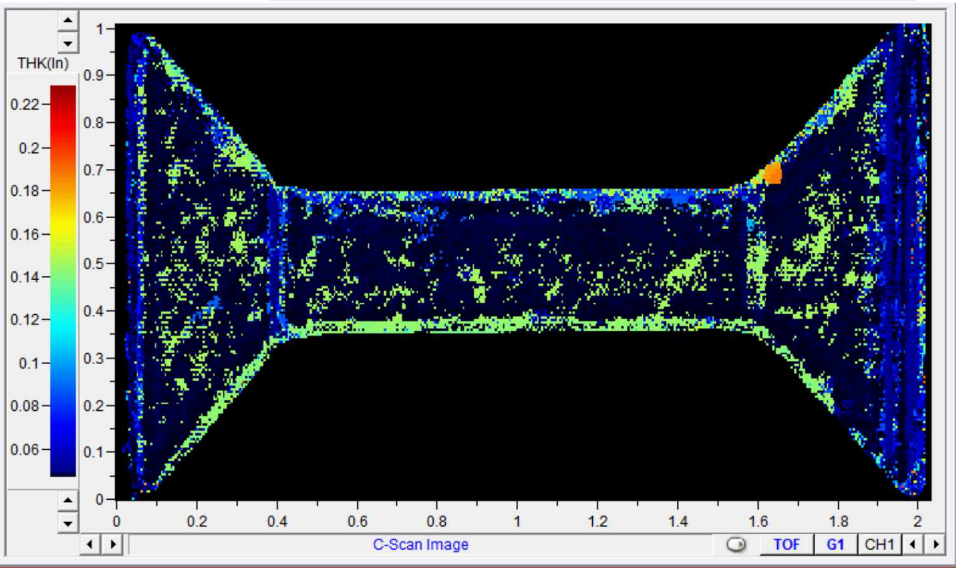
- A porosity analysis was also performed on the CT inspection data and the results are shown at right
- The sample was broken into three regions to increase the computational speed of the porosity analysis
  - Each grip region
  - Gauge region
- Compared to the 2.5 mm thick sample, there is a low porosity content in this 6.25 mm thick sample

Tensile Bar – 6.25 mm Thick

- Pulse echo immersion ultrasound inspection of AM tensile bars
- 30 MHz spherically focused probe
- Focal length = 7.62 cm (3 in.)
- Gate 1 captures the A-scan corresponding to <u>wave propagation through sample thickness</u>

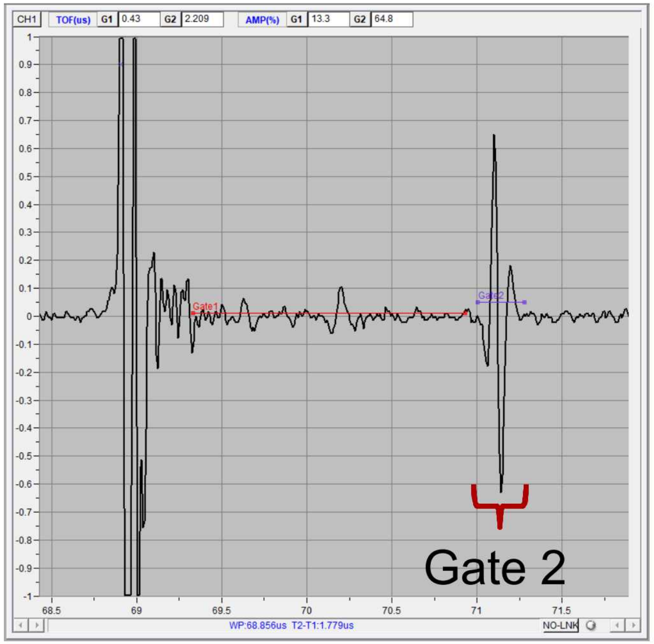


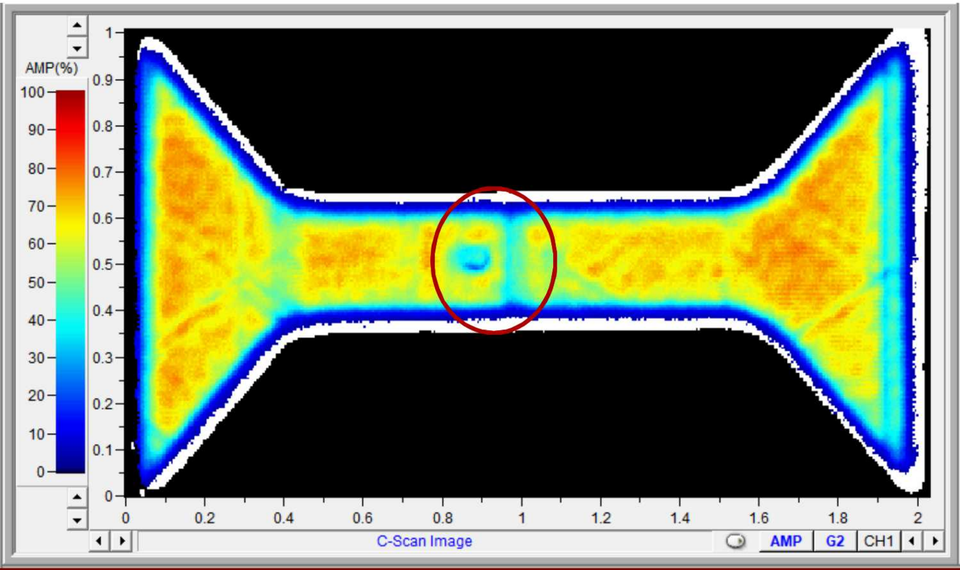


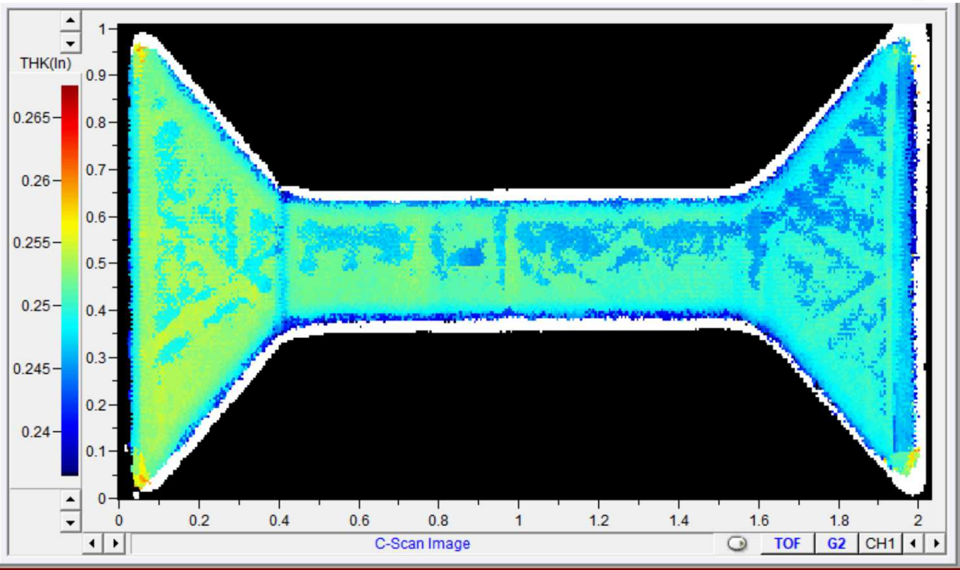


Tensile Bar = 6.25 mm Thick

- Pulse echo immersion ultrasound inspection of AM tensile bars
- 30 MHz spherically focused probe
- Focal length = 7.62 cm (3 in.)
- Gate 2 measures the <u>backwall signal</u>
- Can identify the large groove and steps, but resolving details, such as the depths is difficult







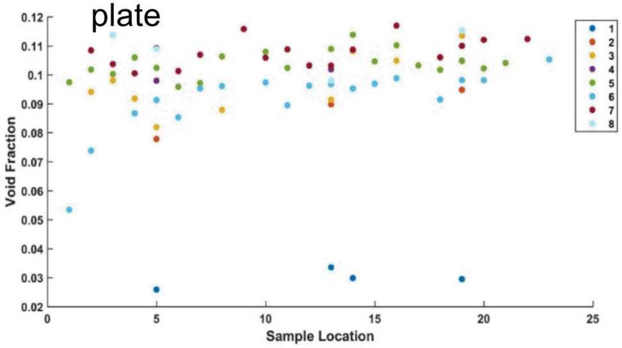
Conclusions

- A variety of additive manufacturing (AM) methods exist for manufacturing components
- Understanding the microstructure of AM parts and how it affects the mechanical properties of the material are critical to qualifying AM parts
- Porosity and the distribution of porosity within a sample affects the mechanical behavior of the part
- Quality assurance of AM materials should include both mechanical testing, such as tensile tests and Charpy impact tests, as well as nondestructive inspection methods
- Computed tomography (CT) and ultrasound inspection are capable of characterizing the microstructure of an AM part. Furthermore, both methods are capable of identifying porosity within the sample, albeit with different visual representations of the results.
- Continued testing on additional batches of AM samples will be performed as we continue to characterize and develop reliable inspection methods for these materials

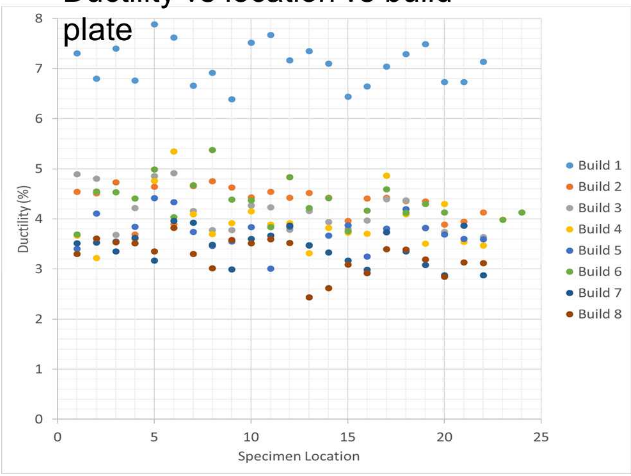
Extra Slides

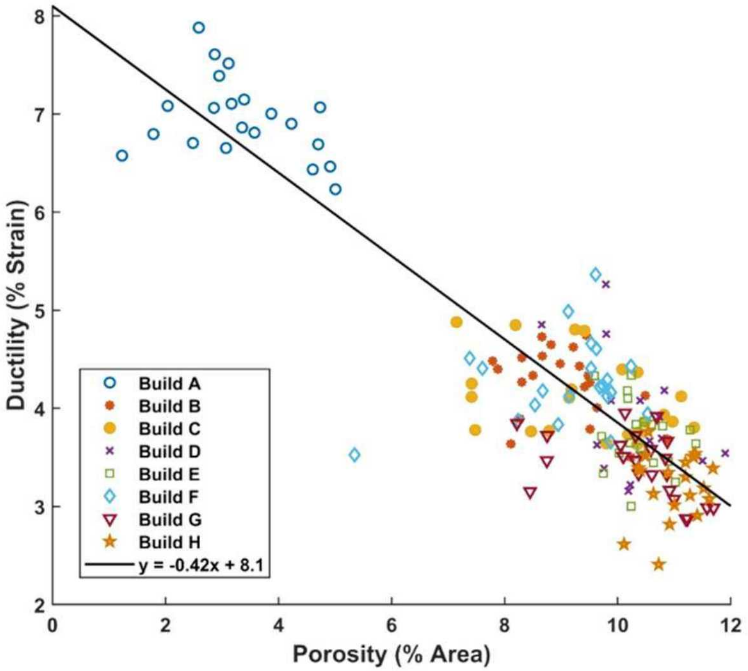
Compare ductility to fracture surface porosity

Porosity vs location vs build plate



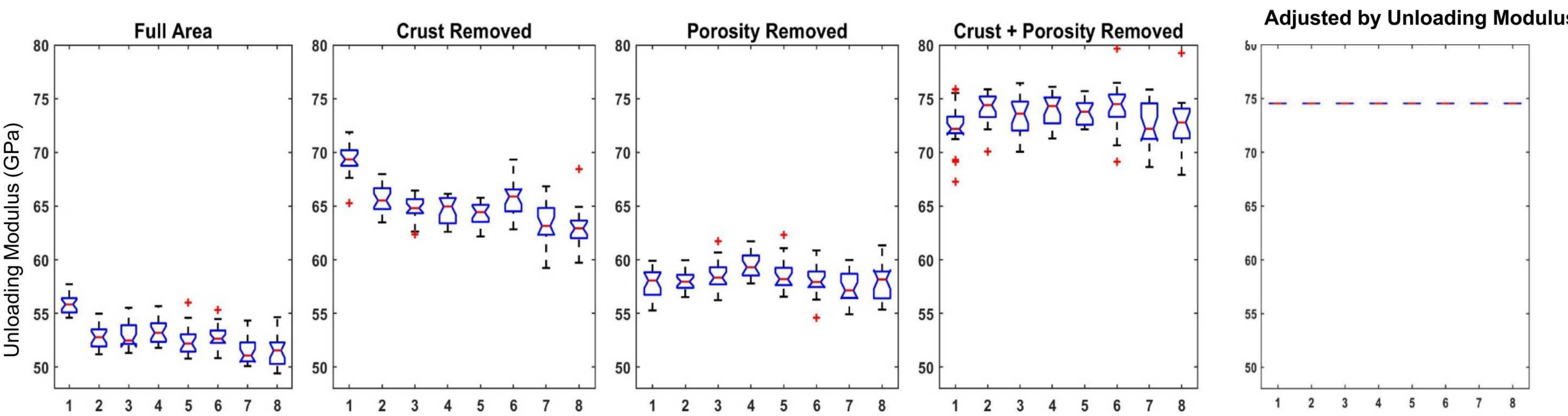
Ductility vs location vs build plate



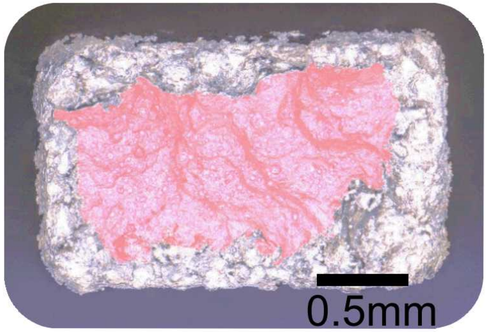


- Increasing fracture surface porosity by 1% decreases ductility by 0.5%.
- Fracture porosity is NOT equivalent to density.
- Relationship between fracture surface porosity and density?

Crust and porosity effects on unloading modulus



- Correct measurements to extract “inherent” material properties.
- Crust has dominant effect, but porosity is also meaningful.
- Subtracting crust and porosity gives an unloading modulus near 74 GPa (ultrasound value).
- Going forward, we can correct area based on unloading modulus.



Tensile Bar – 2.5 mm Thick