NAVAL NUCLEAR LABORATORY | Technology

Embedding Surface-connected Cracks in 316L Stainless Steel Laser Powder Bed Fusion Manufactured Pipe Specimens for Qualification of Phased Array Ultrasonic Testing Inspection Techniques

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Key Takeaways

- Reverse-engineering of existing cracked specimens is possible.
  - Use computed tomography (CT) if you need to keep the specimen intact.
- High-fidelity surface-breaking cracks can be built right into parts to support qualification of ultrasonic testing inspection techniques.
- Computed tomography and metallography are key enablers for reverse engineering and for verification of proper build.

Phased Array UT Technique Qualification Process

1. Identify the component and area within it to be inspected.
2. Choose type, number, sizes, and locations of flaws in accordance with requirements.
3. Create mockups.
    1. EDM Notches
    2. Flawed Vendor Mockups
    3. Additive Manufactured Mockups with Embedded Flaws
4. Verify mockups were made correctly.
    1. Hand scan or record PAUT data as required for all scans on all mockups.
    2. Analyze data for proper presence of flaws.
    3. Use computed tomography (CT) to verify flaws as needed.
5. Give inspectors blind exams in accordance with requirements. Grade and publish results.
6. Perform the inspection.

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AM UT Mockup Creation Process

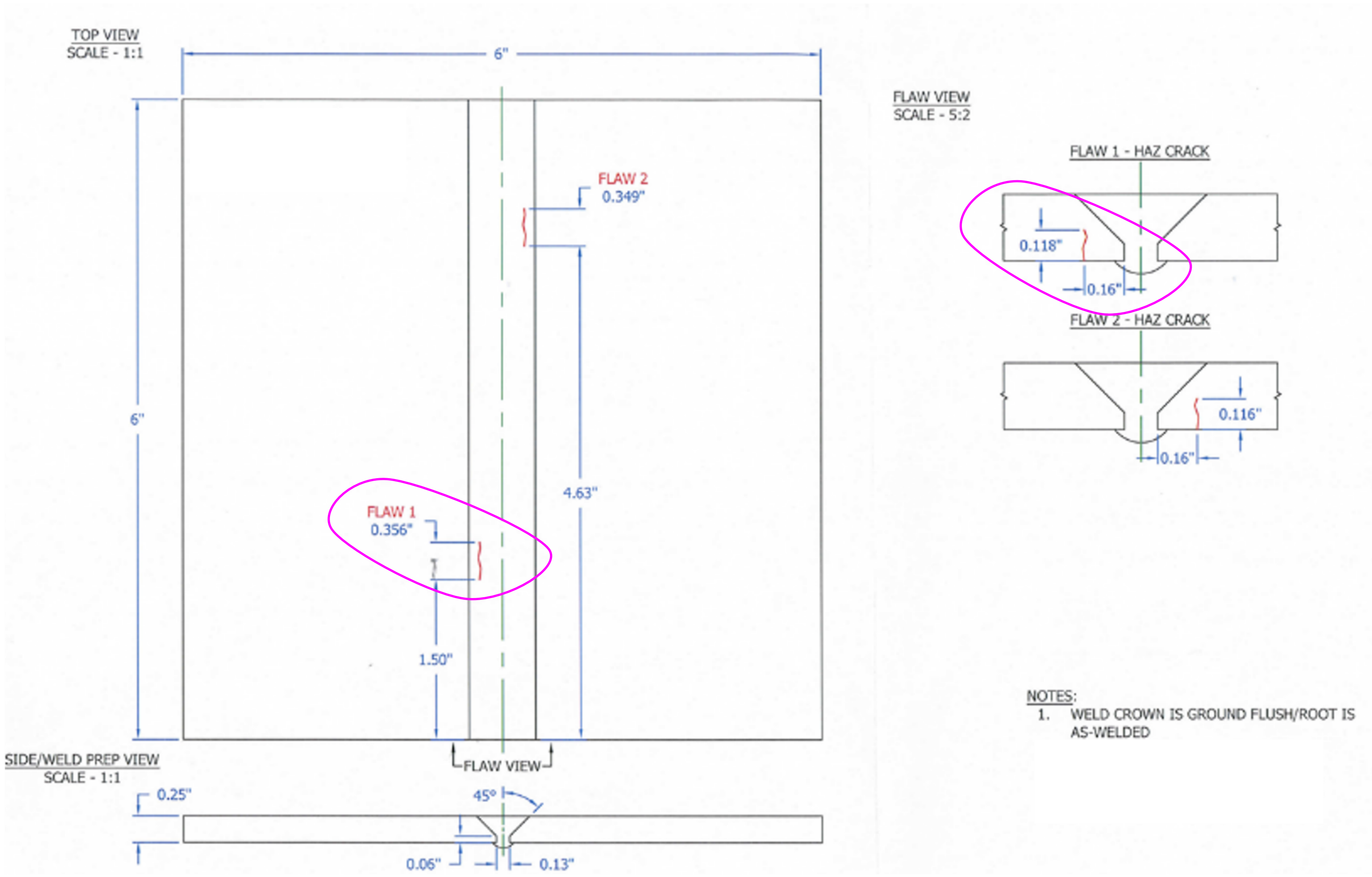
1. Create a 3D model of the part to be inspected (parametric CAD or laser scan).
2. Create and insert 3D models of cracks as voids.
3. Prepare the model for additive manufacturing (AM).
   - Optimize AM parameters (EOS M290)
4. Print the models, remove them from build plate, and smoothly finish all surfaces from which the inspection will be conducted.
5. If possible, verify proper printing of flawed parts using computed tomography (CT).

Method 1: Drawing Cracks Parametrically

1. Review CT or metallography images every 0.020 inches.
2. Manually trace or transpose the crack cross-sections onto sketch planes in a 3D parametric CAD program like Creo Parametric.
3. Extrude each sketch 0.020 inches as a cut.

Creating 3D Models of Cracks

Reverse engineering an off-the-shelf flaw via computed tomography and metallography.

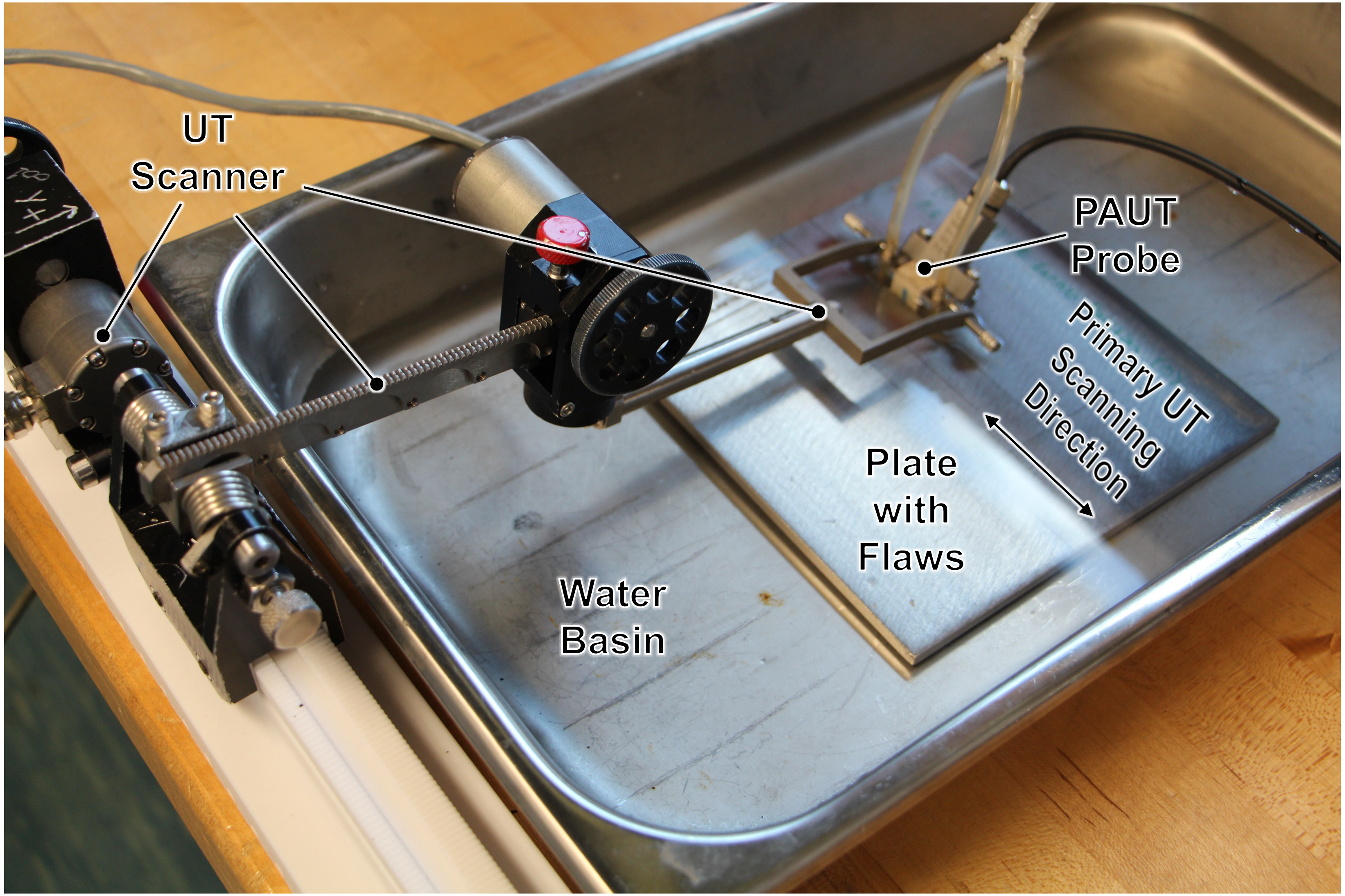


Crack Imaging Process

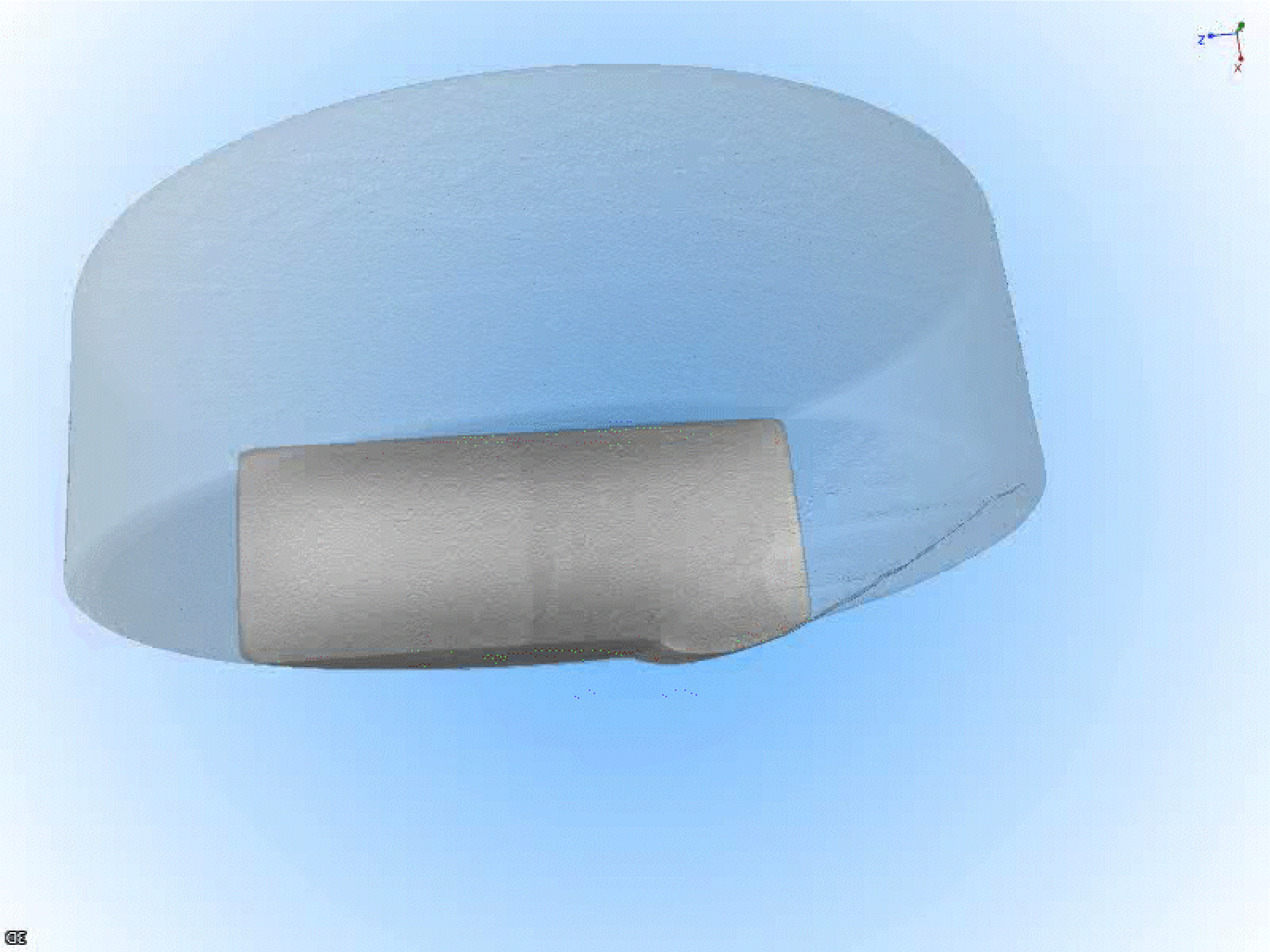
1. Perform a baseline PAUT scan of the plate containing the crack.
2. Cut out a < ¾-inch disk from the plate containing the crack.
3. Scan and analyze via CT.
4. Perform serial grinding metallography to achieve a high-resolution image of the crack at about every 0.020 inches.
    1. Robo-Met has been used to automate this, but materials are still expensive.

PAUT Imaging

Zetec AS-10 MHz on a 55 shear wave wedge, attached to a bidirectional scanner.



Computed Tomography Video

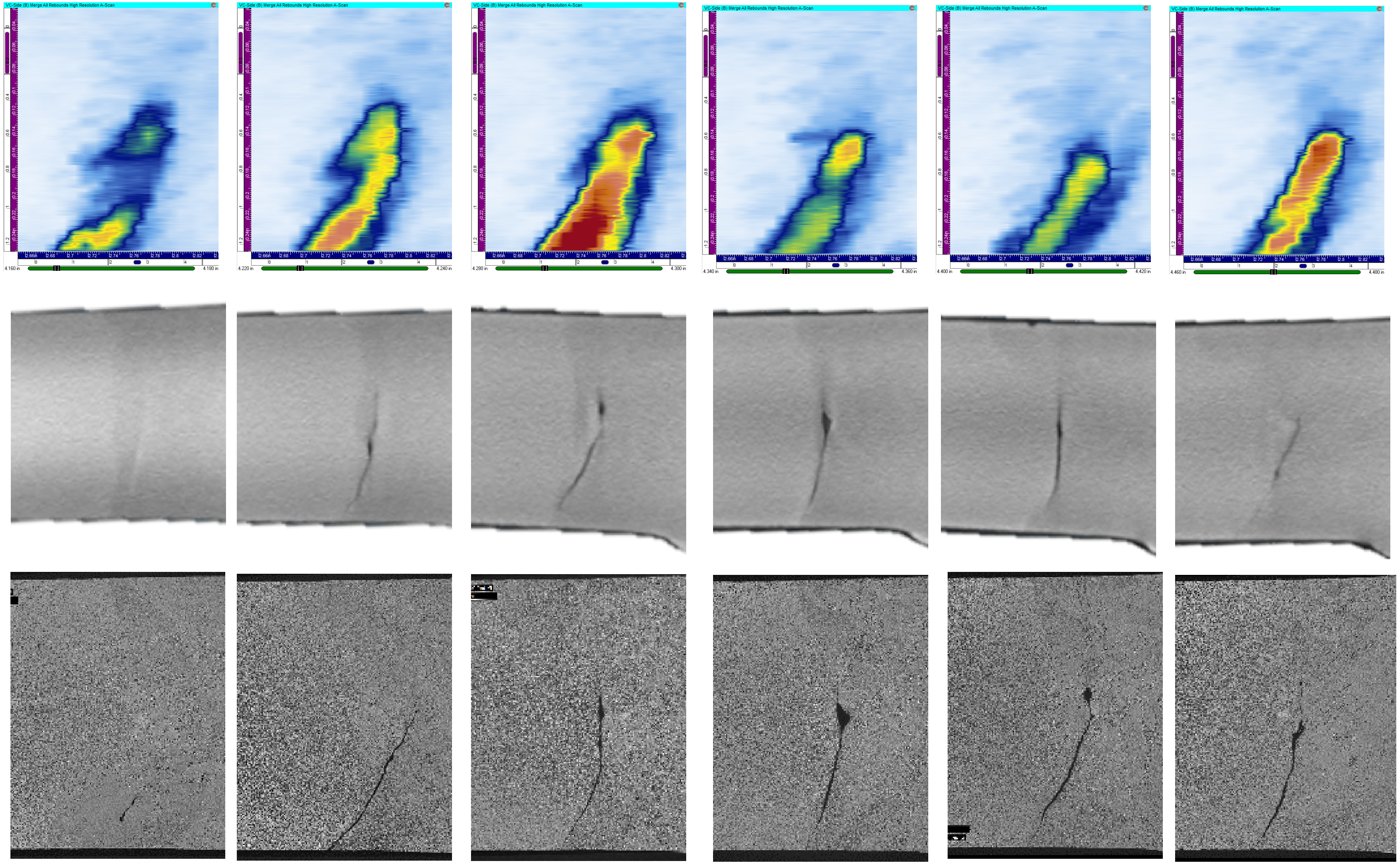


Images taken along the Crack Face every 0.060 inches

PAUT

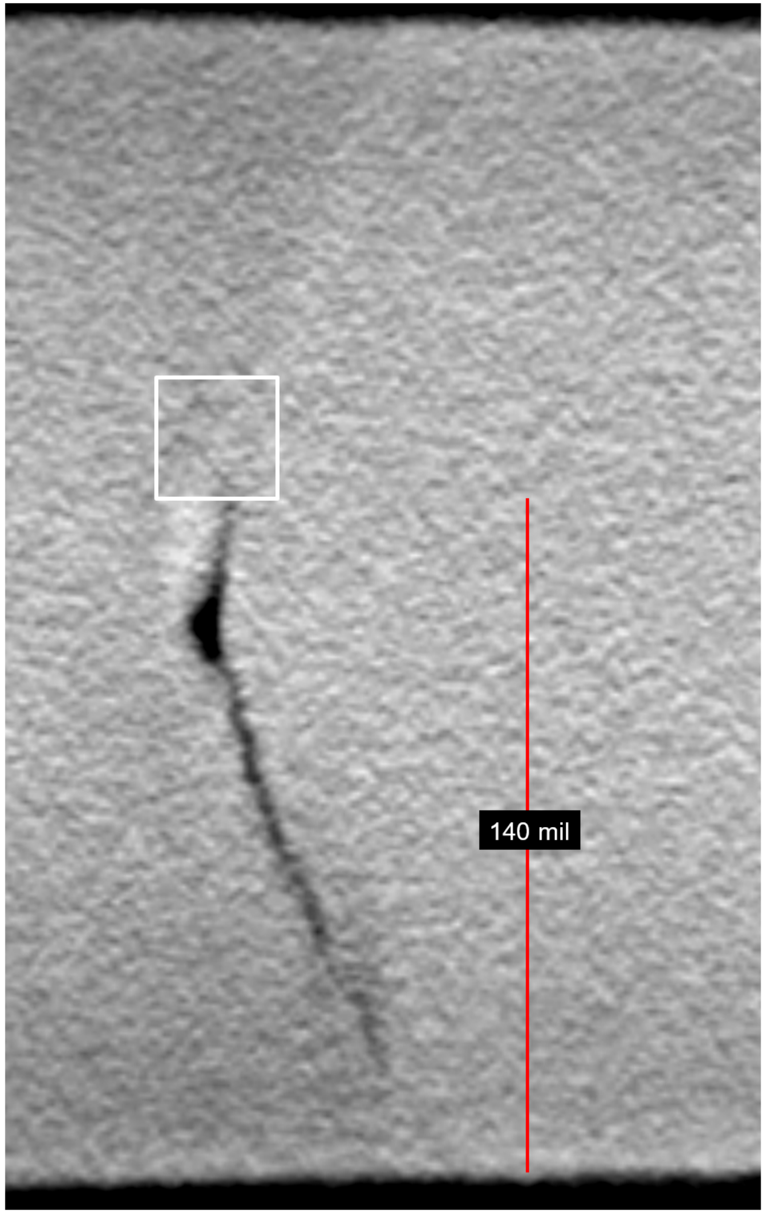
Computed Tomography

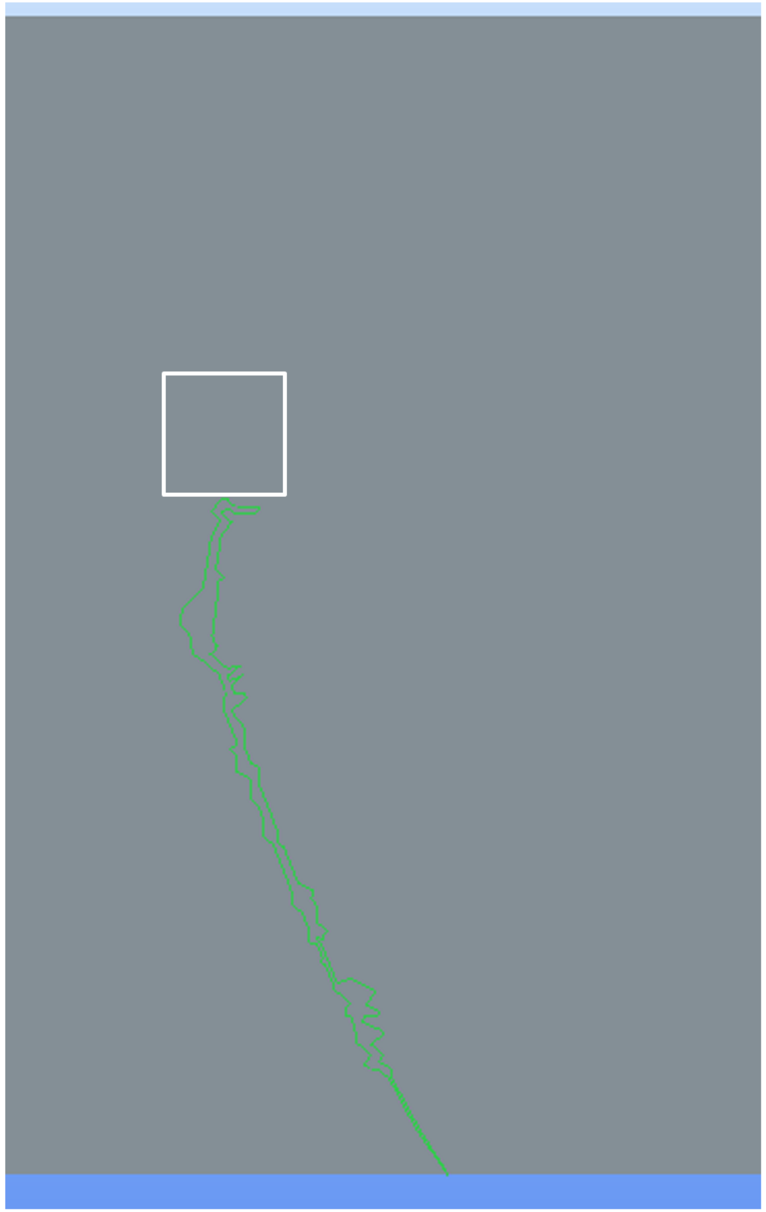
Metallography



Reverse-Engineering an Artificial Flaw

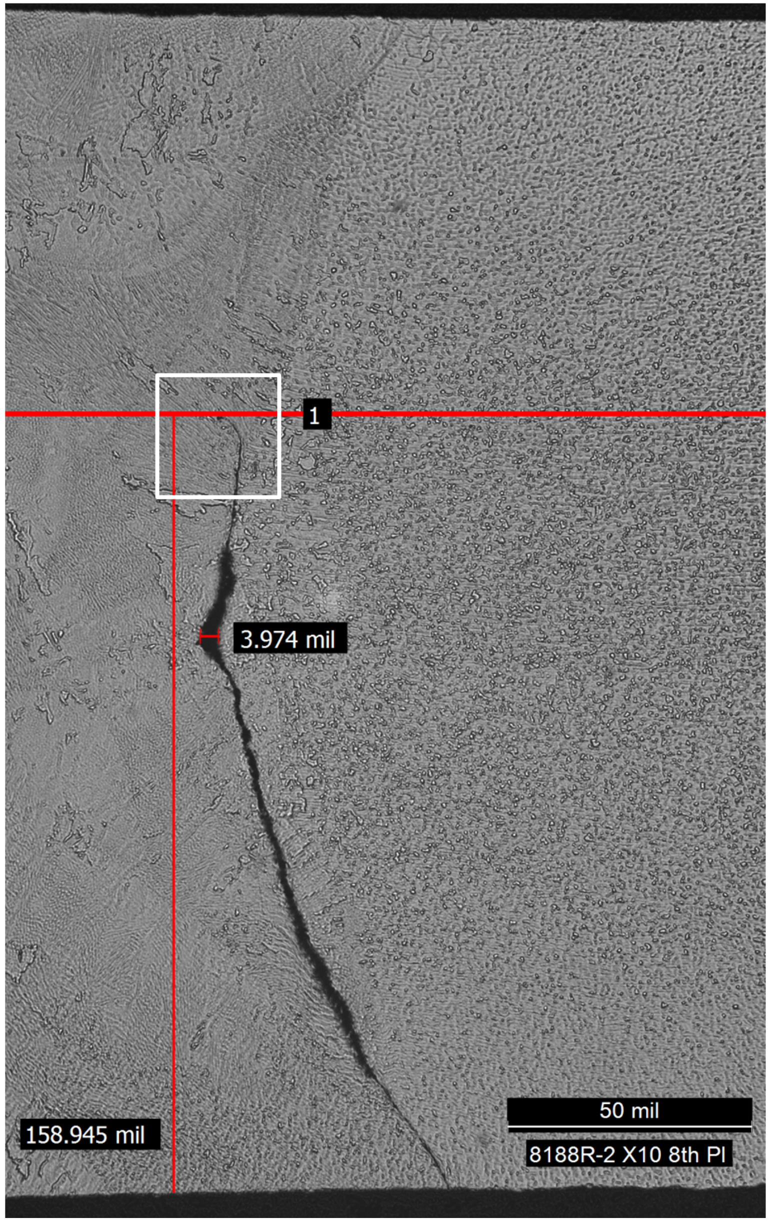
Screenshot extracted from CT data and resulting CAD sketch.

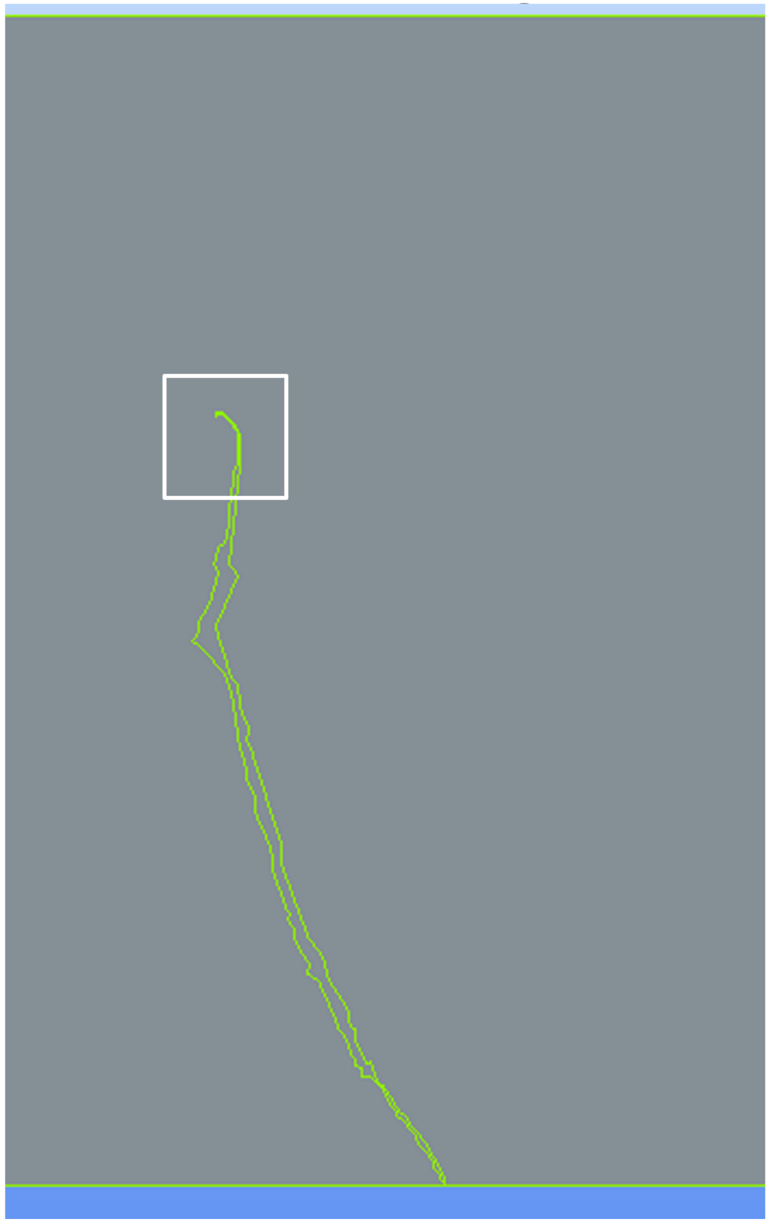




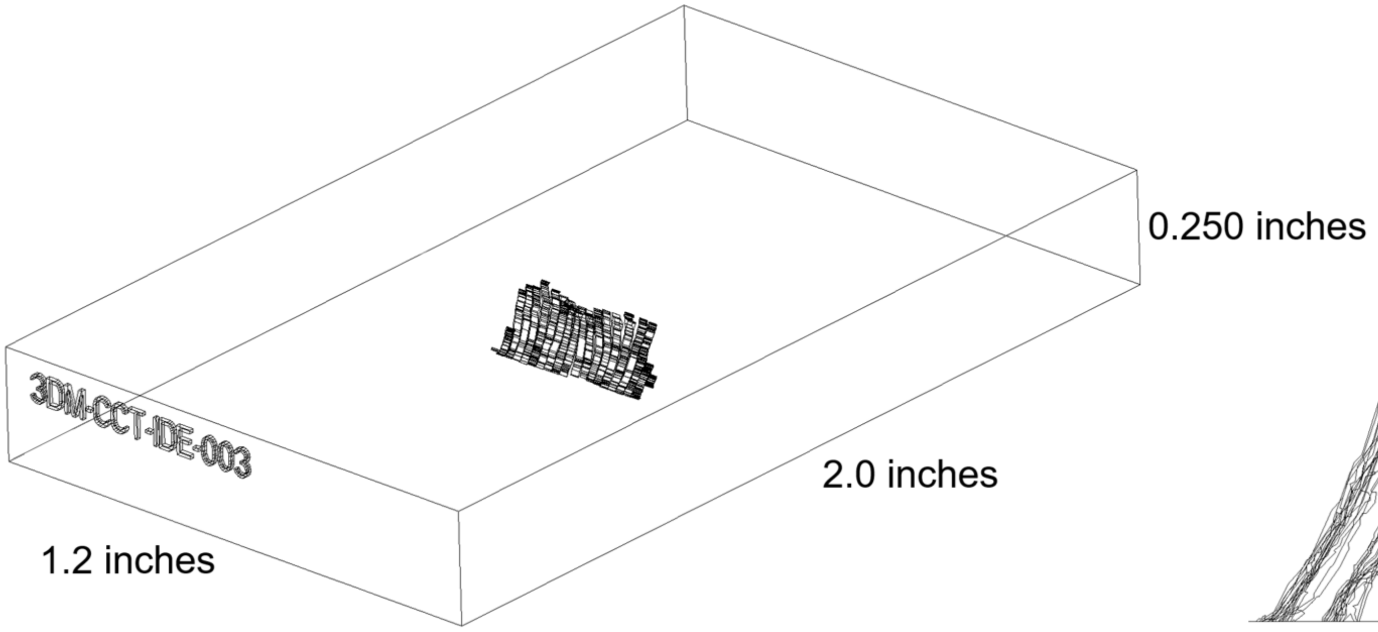
Reverse-Engineering an Artificial Flaw

Metallographic image and resulting CAD sketch.

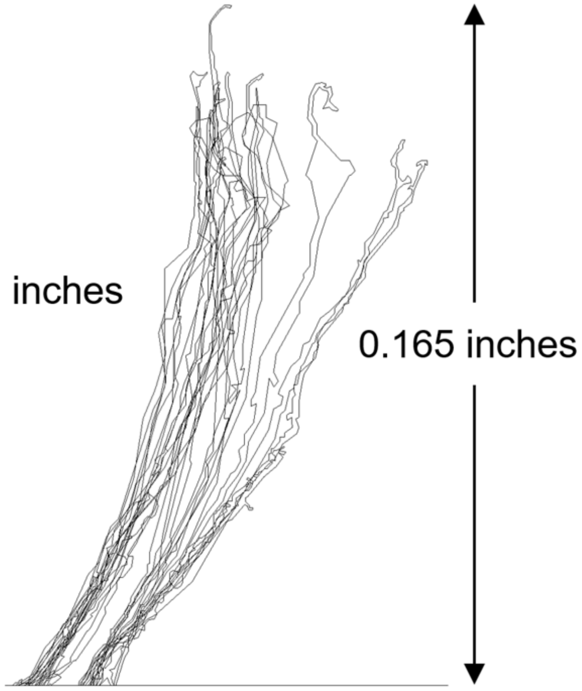




Completed 3D Model of an example Parametrically Drawn Crack

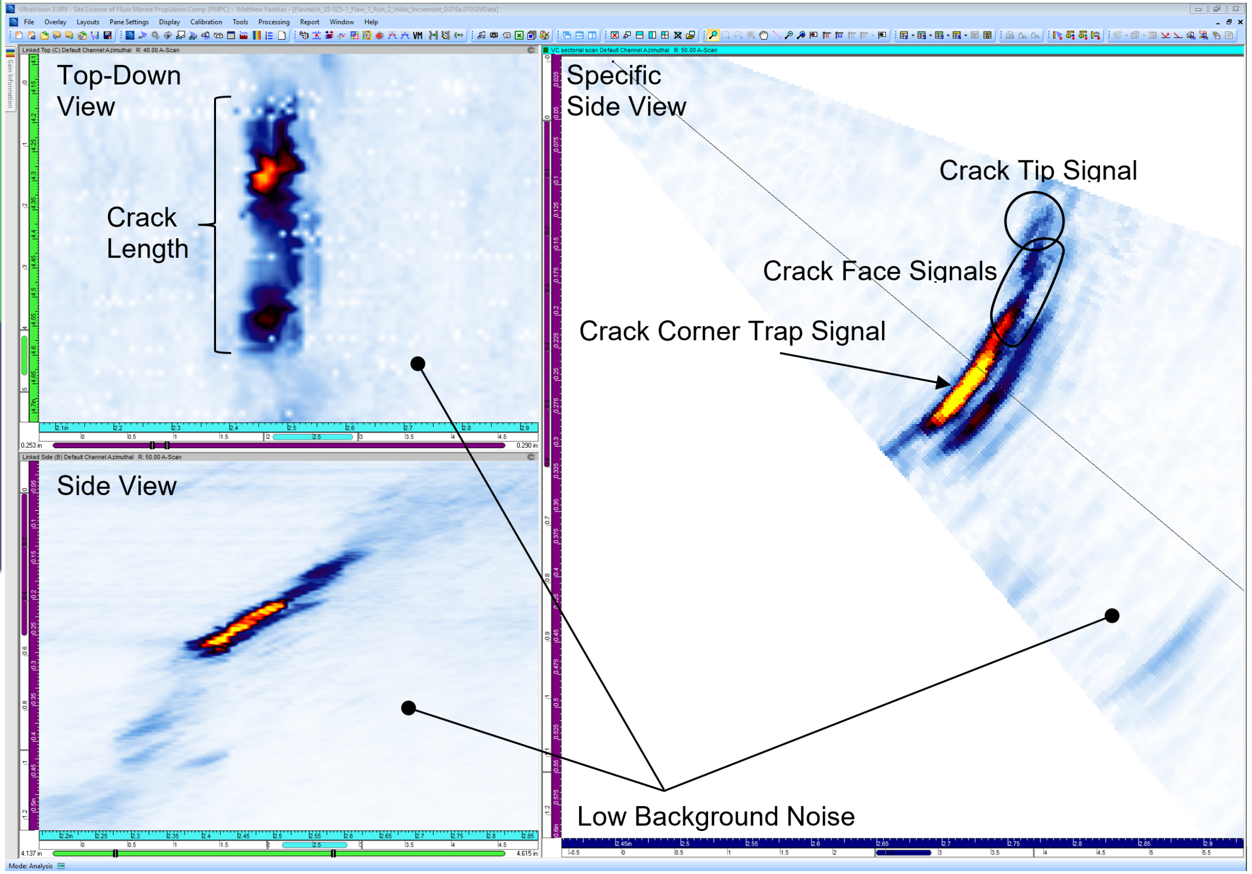


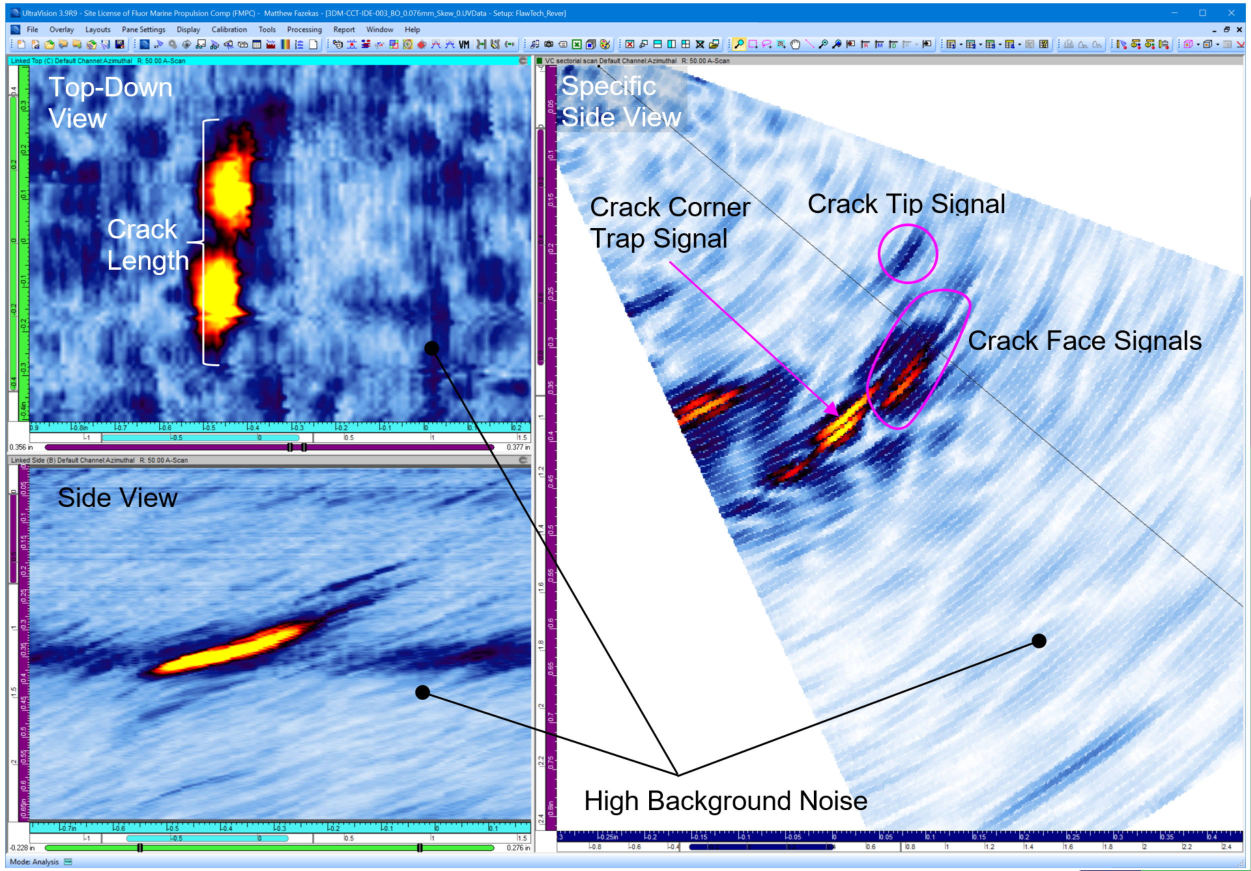
Isometric view



Side view

Phased array imaging is clearer for the original (left), but the flaw is still well imaged in the additively manufactured specimen (right).

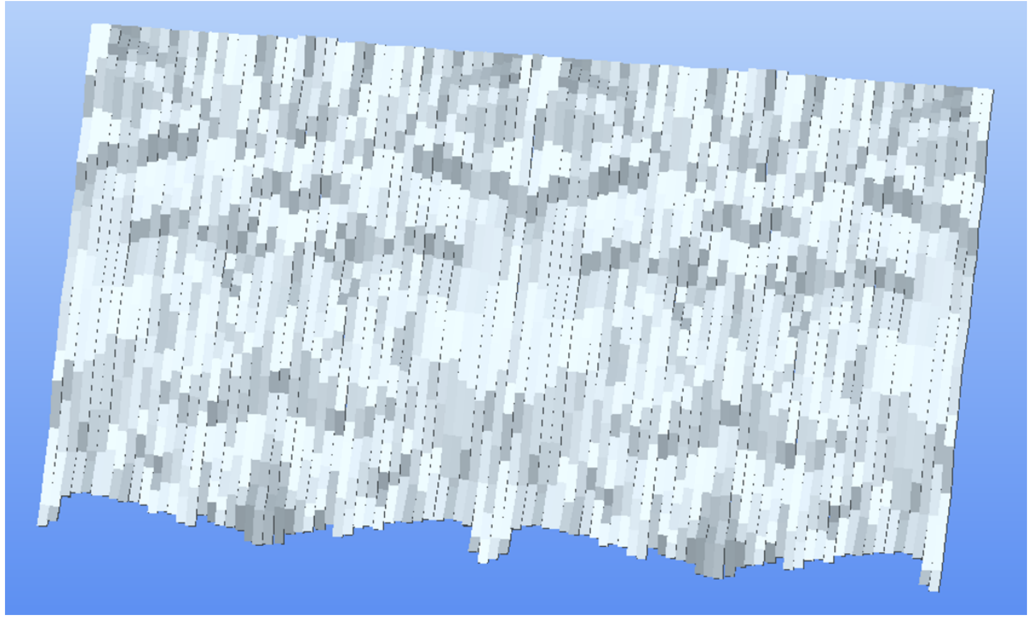


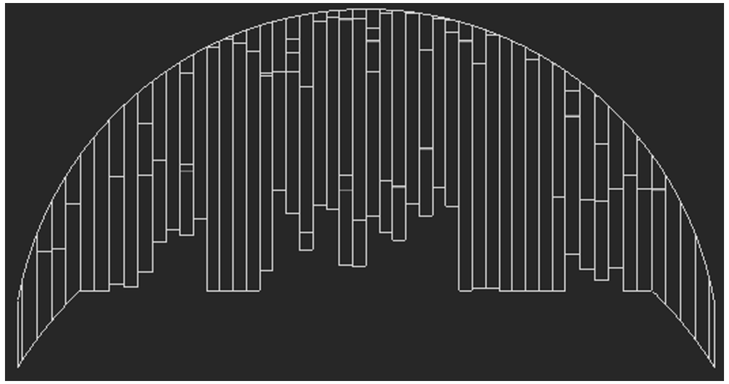


PAUT images generated from the original SS-025-1 sample using a10 MHz transducer.

PAUT images generated from the reverse-engineered 3DM-CCT-IDE-003 specimen using a 5 MHz transducer.

One step further: Designing Crack faces from the Ground Up

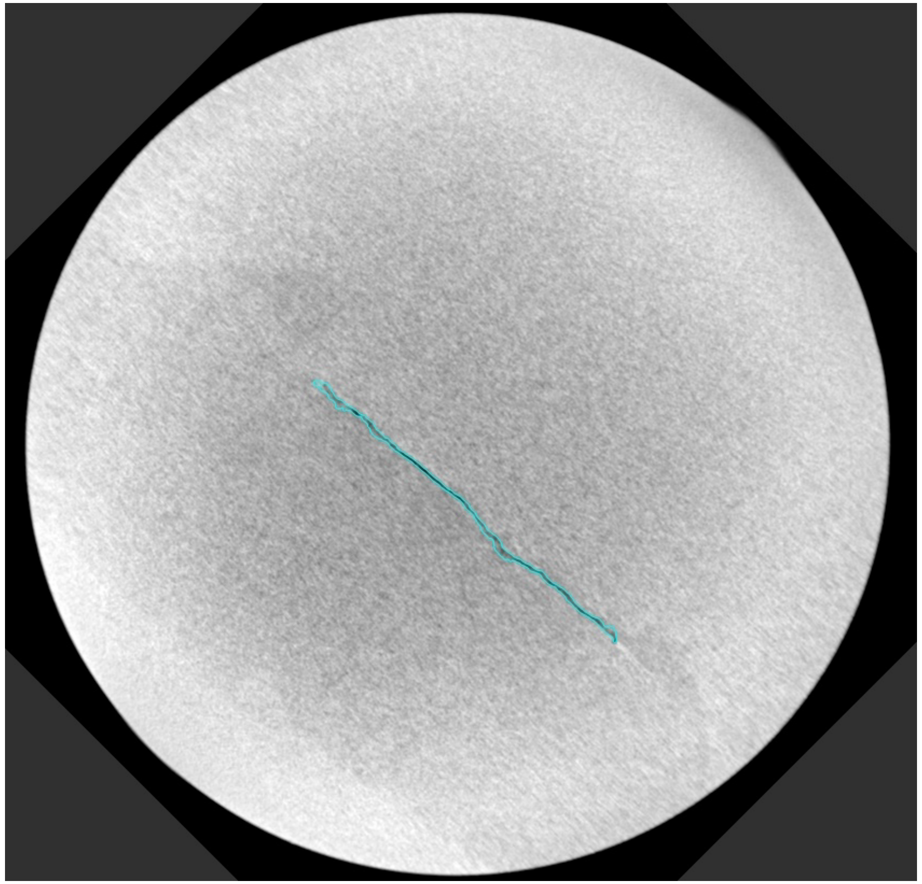


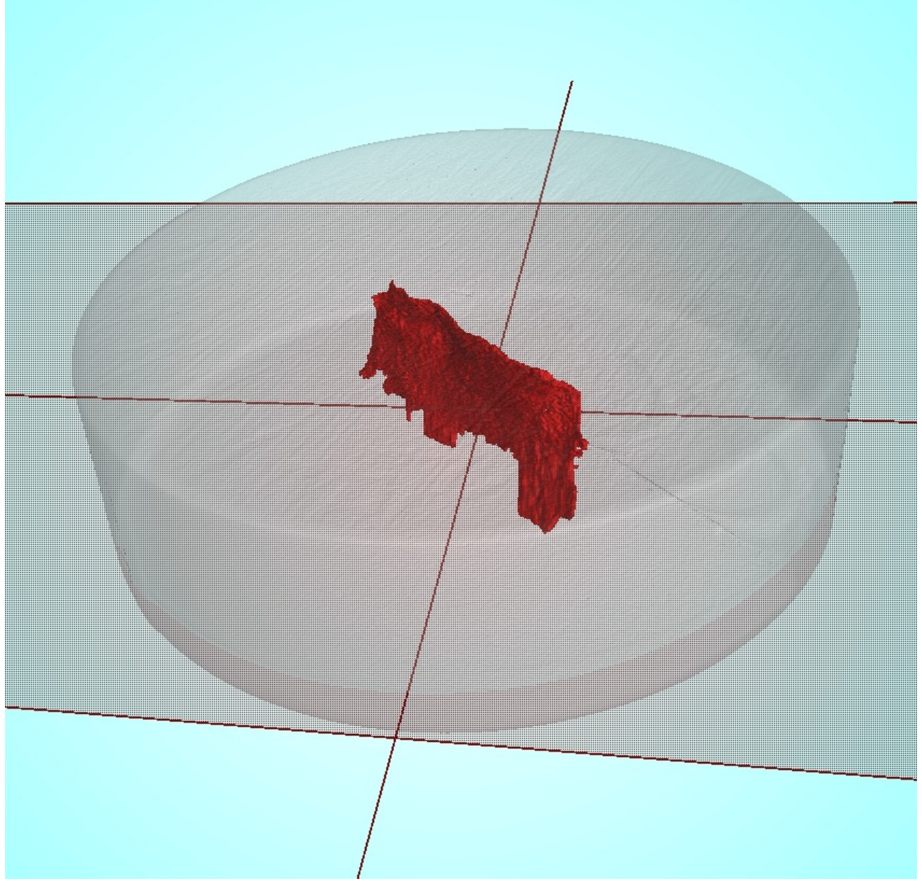


Method 2: Extracting a Crack Face from CT Images

1. Use the CT analysis software to automatically extract the crack features, if sufficient contrast exists.
   - For areas of insufficient contrast, manually identify or draw crack features to be exported.
2. Export as a 3D model.
3. Insert into 3D CAD model of the component as a cut to create void.

Method 2: Extracting a Crack Face from CT Images





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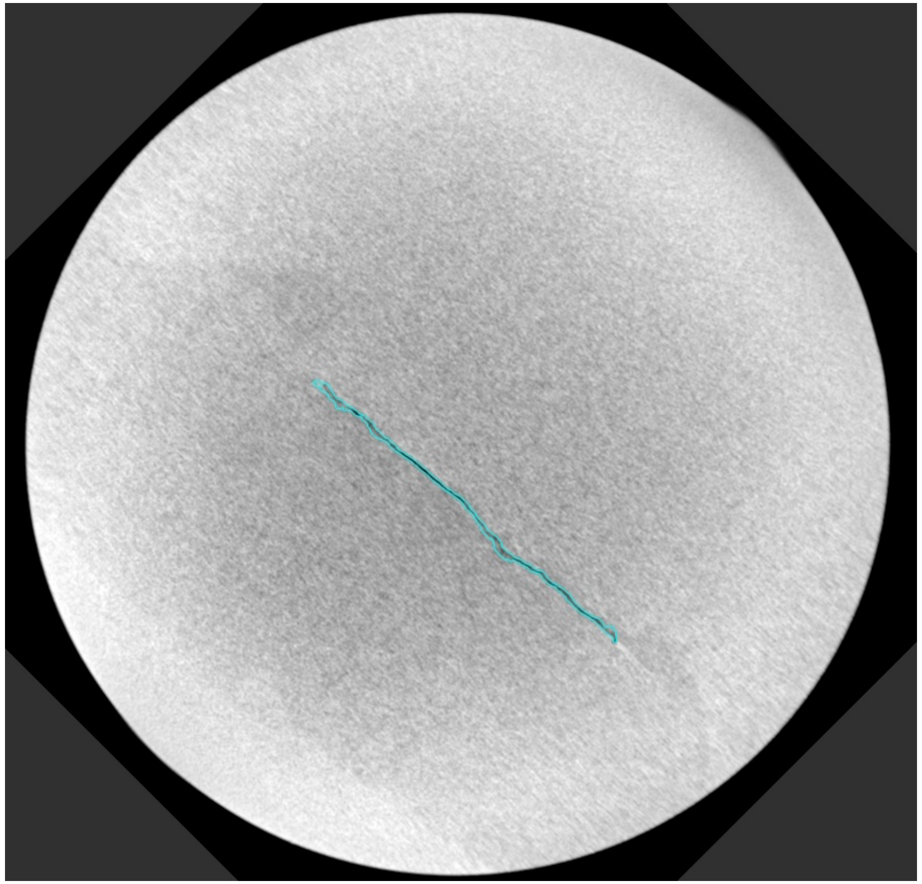
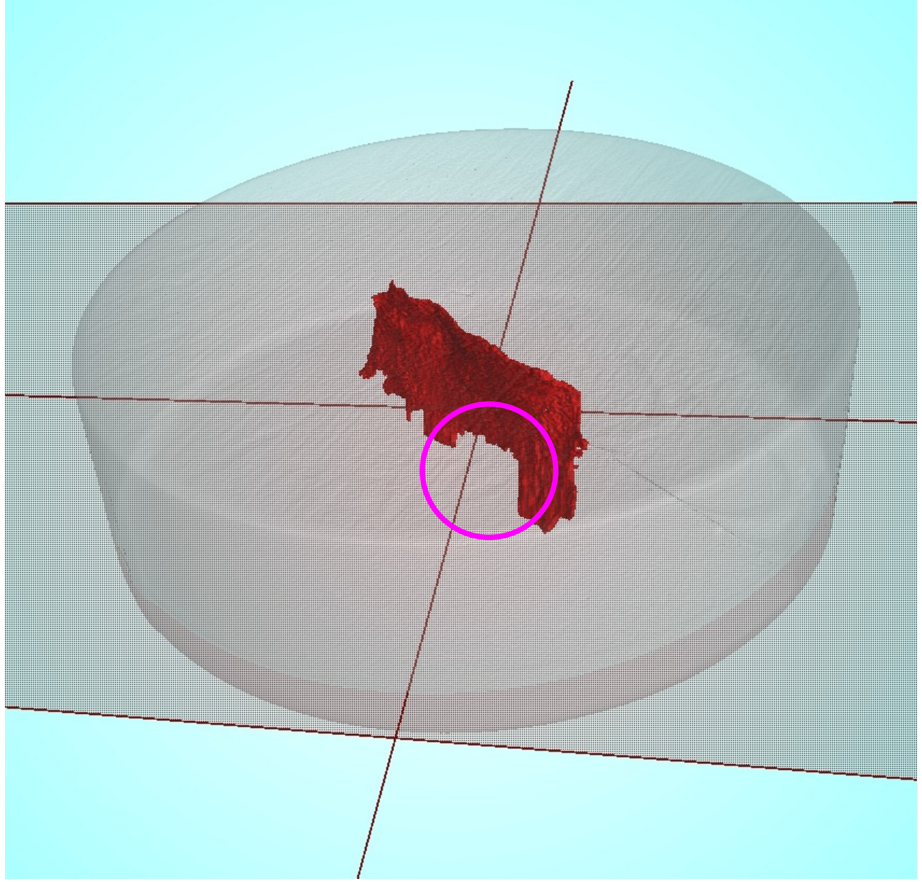
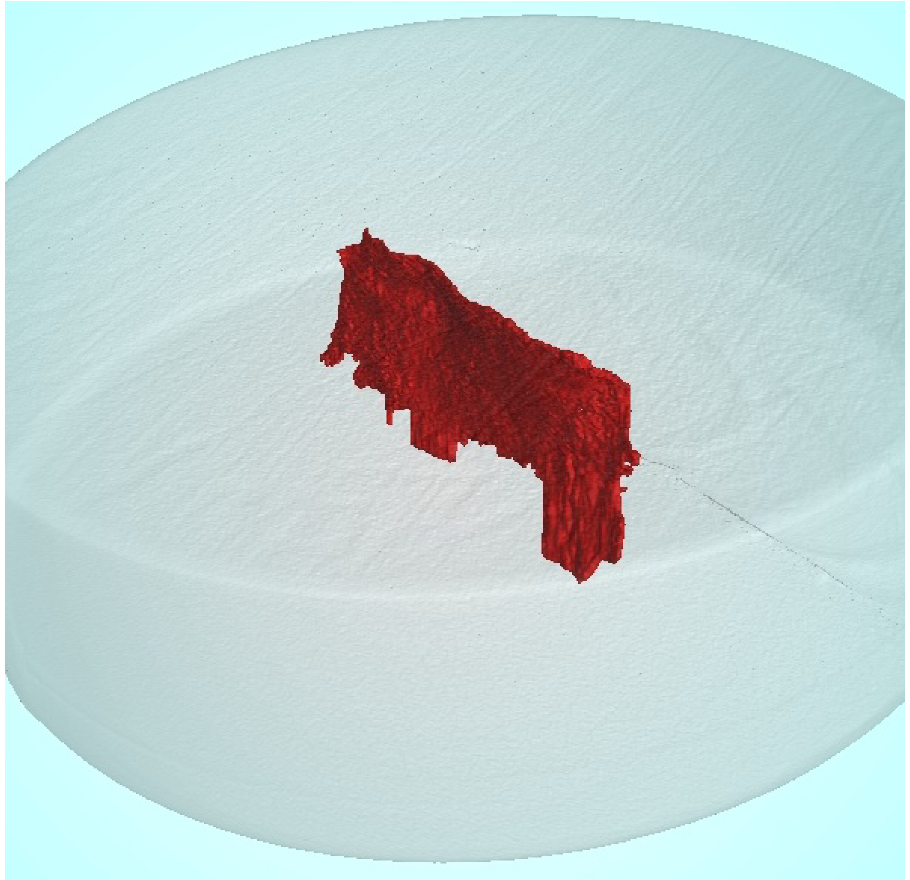
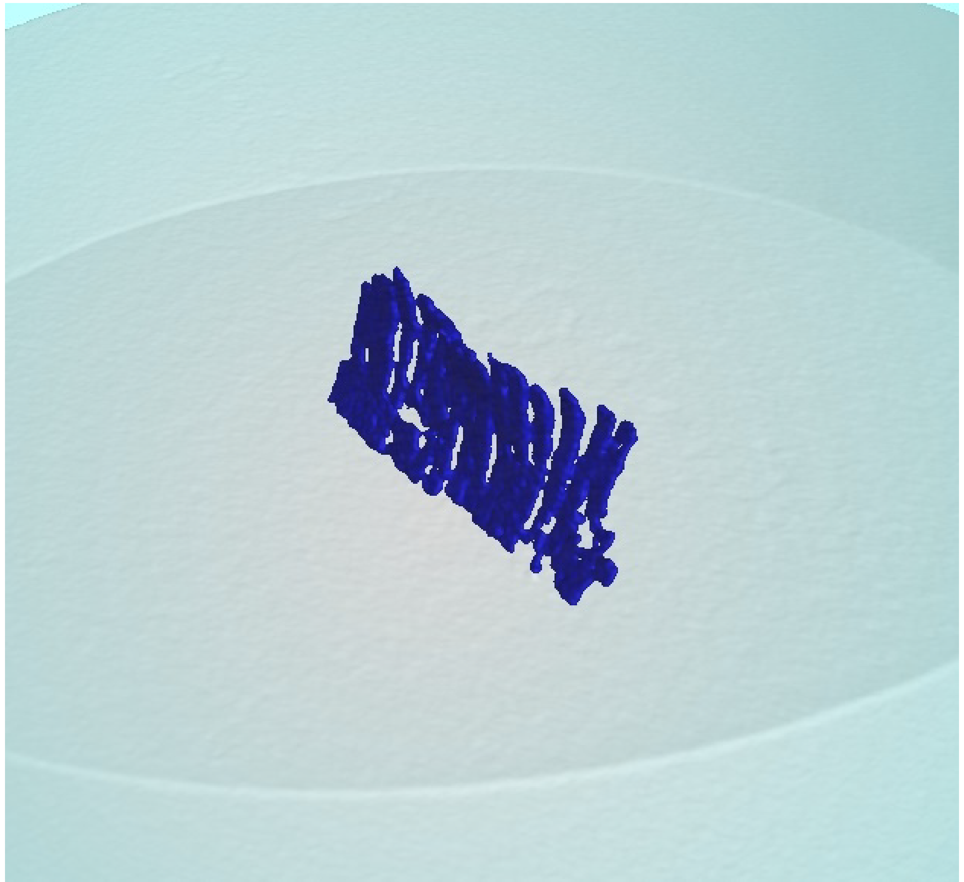




Comparison of Both Methods



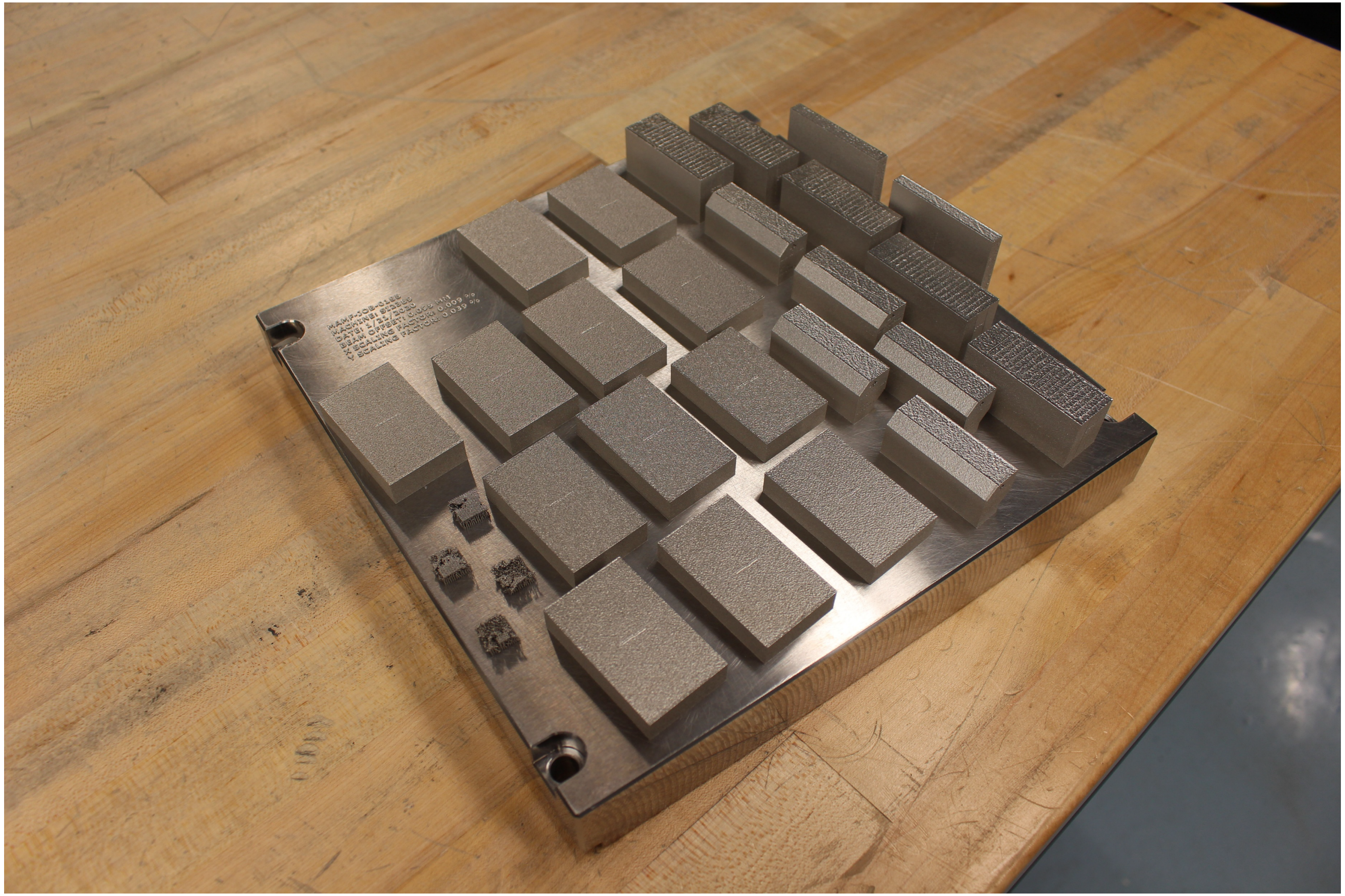
CT image of original crack, showing extracted features.



CT image of reverse-engineered, hand-drawn AM crack

Naval Nuclear Laboratory Metal Additive Manufacturing Facility

Finished Build



EOS M290 Operational Lessons Learned

- The EOS default parameter sets for stainless steel 316L produced acceptable flaws.
  - The 20 um material set (Surface) was preferred due to less anisotropy in the material.
  - The 40 um material set (Flex) was acceptable. It's also much cheaper.
  - For large parts, try making the bulk of the part at 40 um layers but make the sections where UT will be performed of 20 um layers.
- With default settings, the smallest feature size in the X-Y plane is about 0.006 inches.
  - If necessary, reduce the beam offset to make the minimum achievable feature size smaller. A very small (or even a negative!) beam offset will allow for the laser to travel closer to the contour of the part, resulting in smaller flaws. Too tight, and the laser may fuse this region completely.
- The laser melts the uppermost ~100 um (0.004 inches) of powder and metal, so ensure features are >0.004-inches in the Z-direction to prevent remelting.

AM Build Finishing Lessons Learned

- All powder is retained in embedded cracks; some powder is retained in surface-breaking cracks.
  - This has not had an effect relative to ultrasonic testing, but the residual powder can be detected using CT.
- As-built external surfaces are too rough for PAUT.
  - Smoother parts are better for PAUT.
  - Add 0.020 inches to the outer diameter to parts that can be turned on a lathe.
  - Walnut shell blasting and wet sanding also work to finish parts.
- Verify parts and flaws are printing correctly via CT (where possible) and destructive evaluation.

3D Model Lessons Learned

- If working in a parametric modeling software, use parametric models when possible– they’re much easier than working with meshes generated by 3D scanning.
  - Start with laser scans but abstract a representative parametric 3D model from them.
- Model a large section of crack, like a rectangle. Cut out what you need then implant what need in your part.
  - Draw each crack slice in 0.020-inch extrusions
  - Avoid beginning each crack slice sketch with lines that are perfectly perpendicular to the ID surface; this does not represent cracks very well.
  - Make each crack slice parallel to each other, not radially aligned.
- Include a printable 0-degree mark on each model.
- Include a printable unique identifier for each model.

PAUT Lessons Learned

- Print a set of open practice mockups to allow for training of new inspectors prior to qualification testing.
- EOS default 20 um (Surface) material sets result in a greater chance for isotropic material properties, including shear-wave speed of sound.
- EOS default 40 um (Flex) material sets cuts the build time by about 50%, which can reduce the cost.
- AM mockups are less expensive overall, particularly for small mockups where many can be printed on one build plate.
- Because AM flaws can be put anywhere, make sure they are in places that stand a reasonable chance of detection via UT; don't put a small flaw in the shadow of a larger one.

Acknowledgements

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- Jessica Yeager
- David Driggers
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- Kerry Michaels
- Jonathan Hollis

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Contact Information

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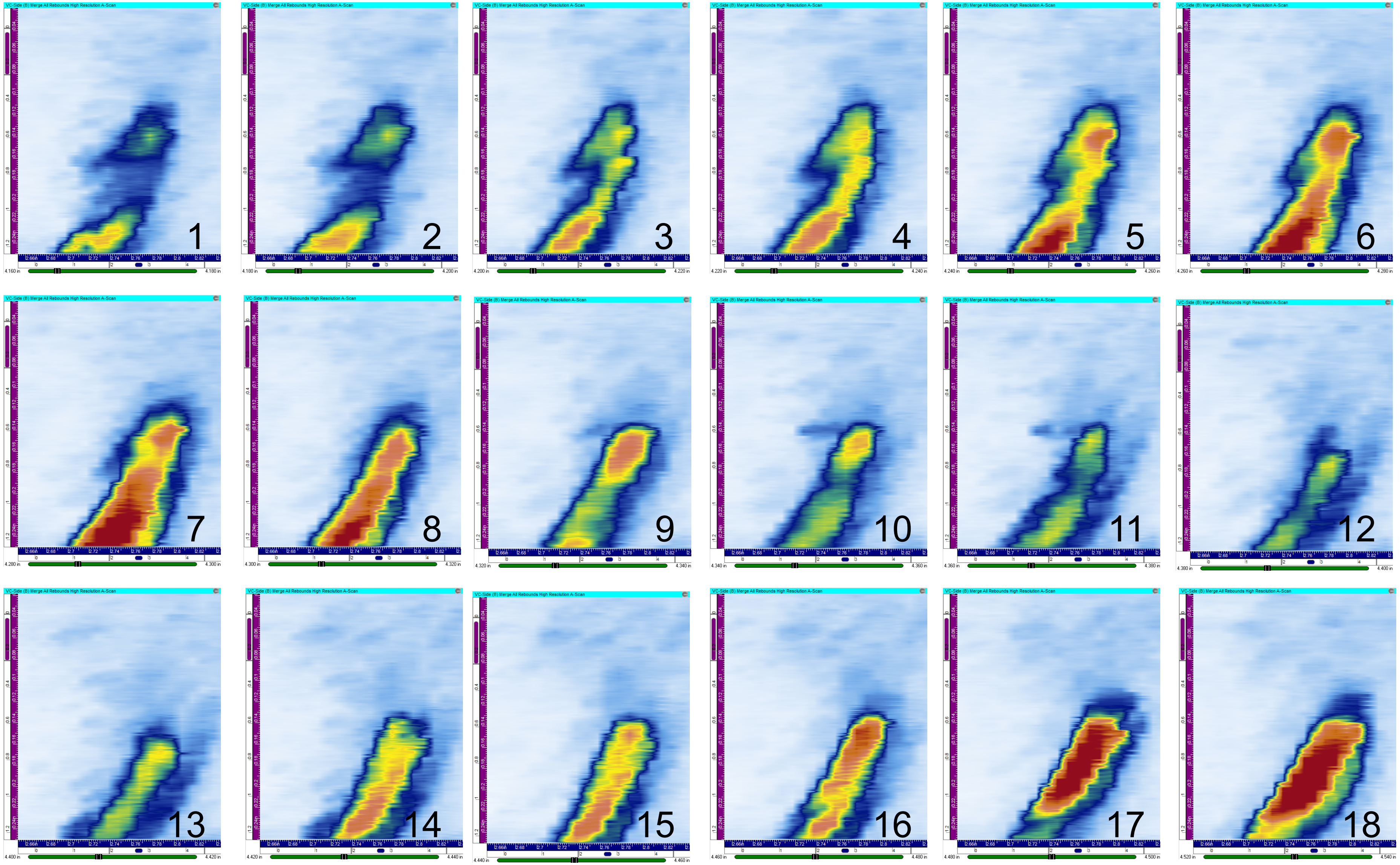
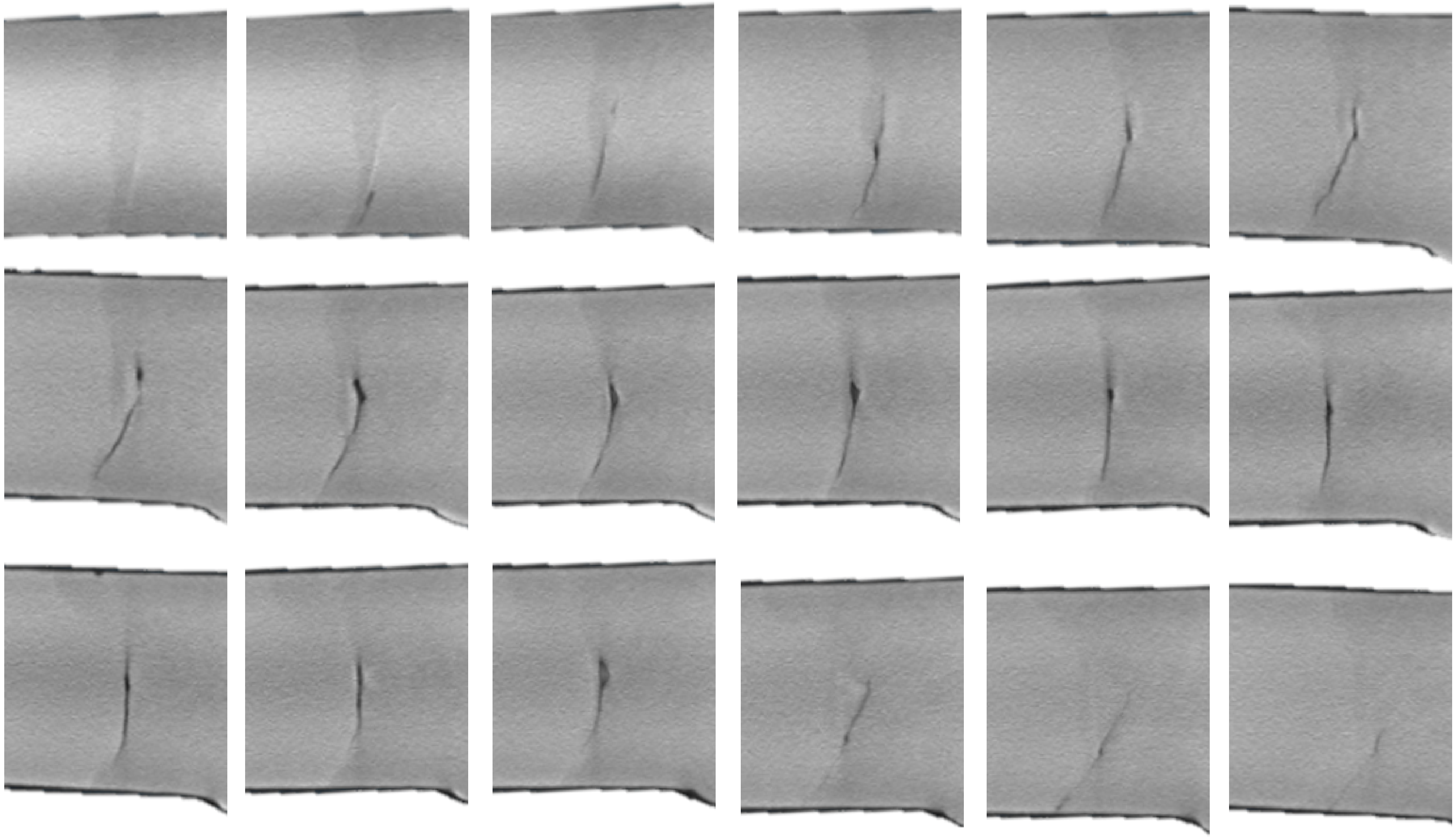
Backup Slides

Merged PAUT Images



Computed Tomography Images



Metallographic Images