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Nondestructive Examination of Electron Beam Welds for Nuclear Pressure Vessel Applications

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2025 NDE Technical Information Exchange

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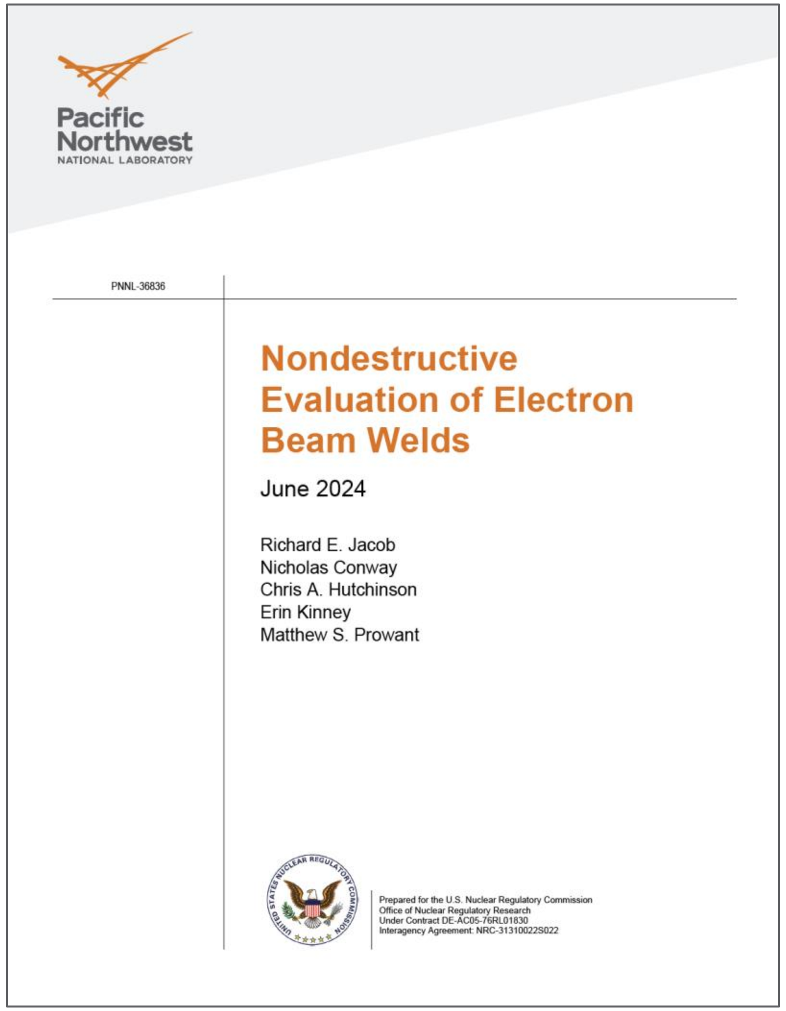
Objective and Scope

- Advanced Manufacturing Technologies (AMTs) are being used globally in many industries.
- The U.S. nuclear power industry has shown growing interest in using AMT components for new plant construction and repair and replacement activities.
- There are currently no nondestructive evaluation (NDE) standards to guide the inservice inspection of AMT components, nor is it known if new standards are needed.
- The objective of the work is to perform confirmatory testing for the Nuclear Regulatory Commission (NRC) on relevant AMT materials to understand which NDE methods and techniques will be effective for inservice inspection.
- The scope of this project is to evaluate NDE methods and techniques on a variety of nuclear-relevant AMT samples and mockups.
  - Evaluate inspectability (e.g., ultrasonic penetration, attenuation, scatter, and frequency response)
  - Evaluate flaw detectability
  - Determine capabilities and limitations of different NDE approaches

Report on NDE of Electron Beam Welds (EBW)

- PNNL report on NDE of EBW (ML24327A005)
- Key findings:
  - The TOFD-style approach was the superior UT method for both detection and sizing
  - Full matrix capture (FMC) showed corner echoes from unfused sections but did not give depth information
  - The tandem approach showed the lack of fusion defects but did not give corner echoes or depth information
  - Radiography was not helpful due to the planar weld geometry and tight opening dimensions of the defects
  - Heat treatment reduced attenuation through the weld, but heat treatment is not necessary for the sole purpose of improving inspectability


Pacific Northwest NATIONAL LABORATORY

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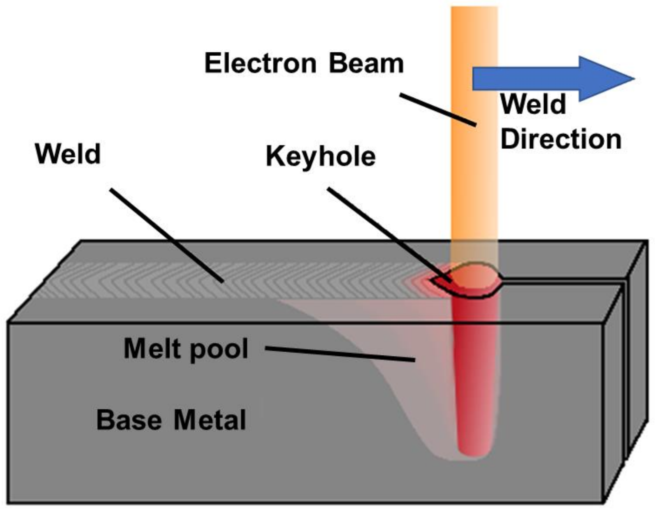
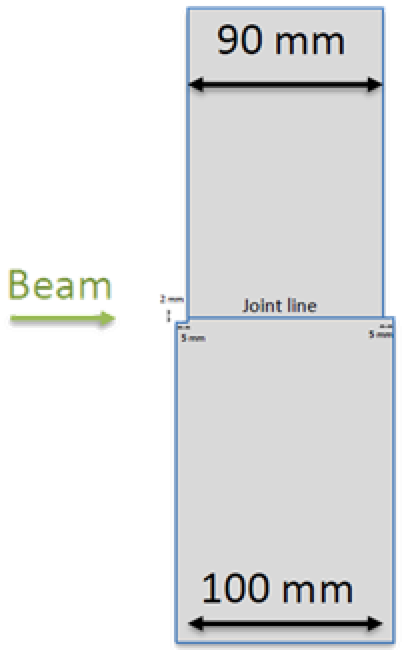
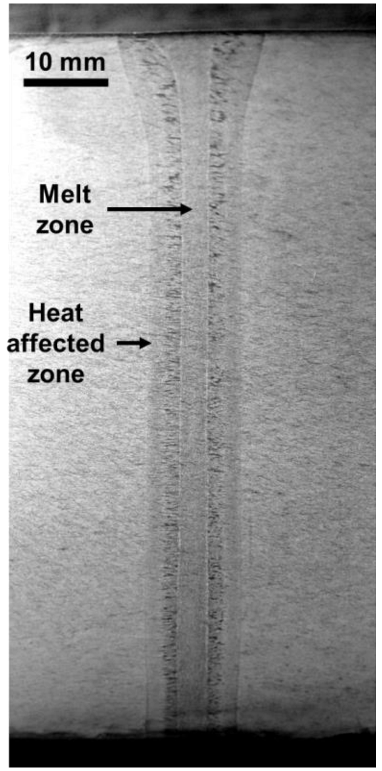
Electron Beam Welding Mockups

- The NRC considers EBW to be an advanced manufacturing technique in the nuclear power industry.
- PNNL evaluated four EBW plate mockups on loan from the Electrical Power Research Institute (EPRI).
  - Made by Nuclear Advanced Manufacturing Research Centre in Sheffield, U.K.
  - Single-pass simple square butt welds with no filler metal
  - Carbon steel (ASTM/ASME SA508 Grade 3 Class 1), 100 mm thick plate welded to 90 mm thick plate
  - All mockups were manufactured from the same billet

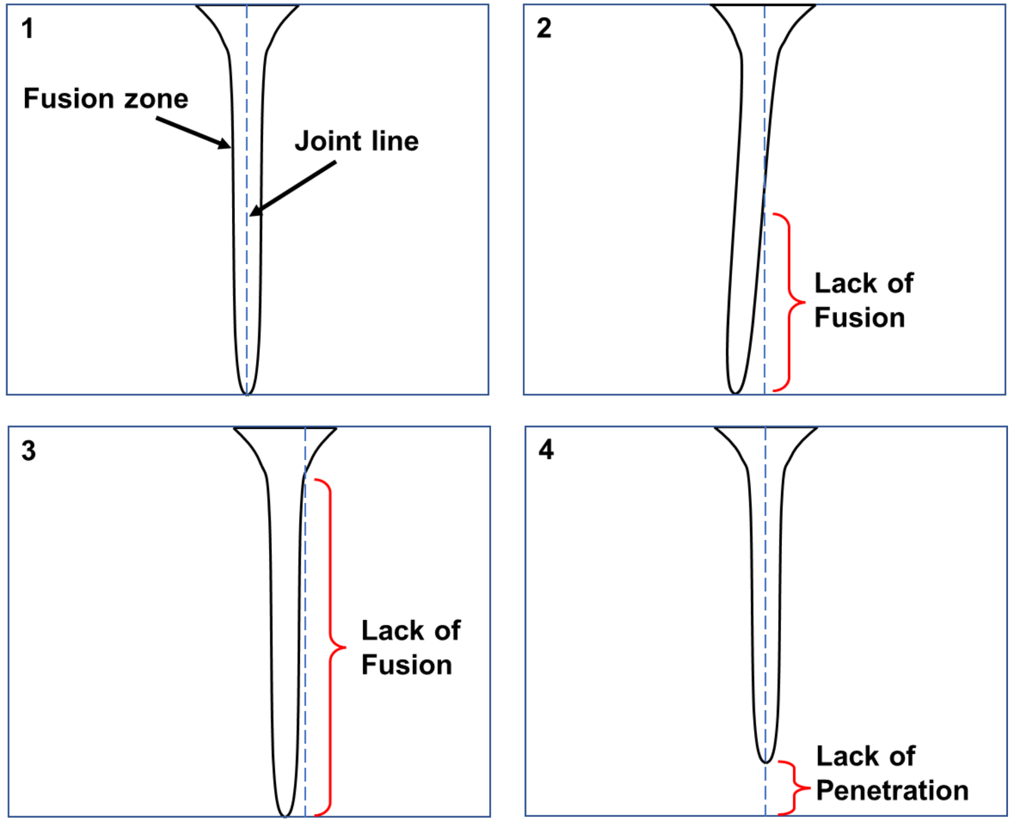






Mockup Defects

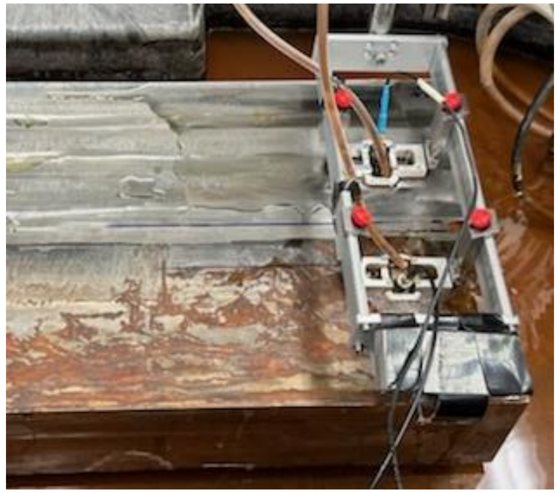
- Of the four mockups, three had intentional defects:
    1. Defect free, built using ideal weld parameters
    2. Partial lack of fusion caused by beam deflection and full-thickness keyhole defect due to a beam shutdown
    3. Large lack of fusion (LOF) caused by poor beam settings
    4. Lack of beam penetration (LOP) along full length of the weld



NDE Performed at PNNL

- X-ray radiography
- Encoded pulse-echo ultrasonic testing (UT), 0°
  - 10 MHz
  - From one edge of the plate toward the weld for weld characterization
- Encoded pulse-echo FMC (full matrix capture) UT
  - 3, 4, and 5 MHz shear, TT-mode
  - Both sides of the weld
  - Both sides of the plate (top and bottom)
  - Prior to machining plates smooth
- Encoded pitch-catch TOFD (time of flight diffraction) UT, 45° shear
  - 5 MHz
  - Both sides of the plate
  - After plates machined smooth
- Encoded pitch-catch tandem UT, 45° shear
  - 5 MHz
  - ≈1.5 inch probe separation
  - Both sides of the weld
  - One side of the plate (scanned from top only)

Plate 1, as received. After the FMC scans, the plates were machined smooth to a uniform 90 mm thick



TOFD setup

Tandem setup

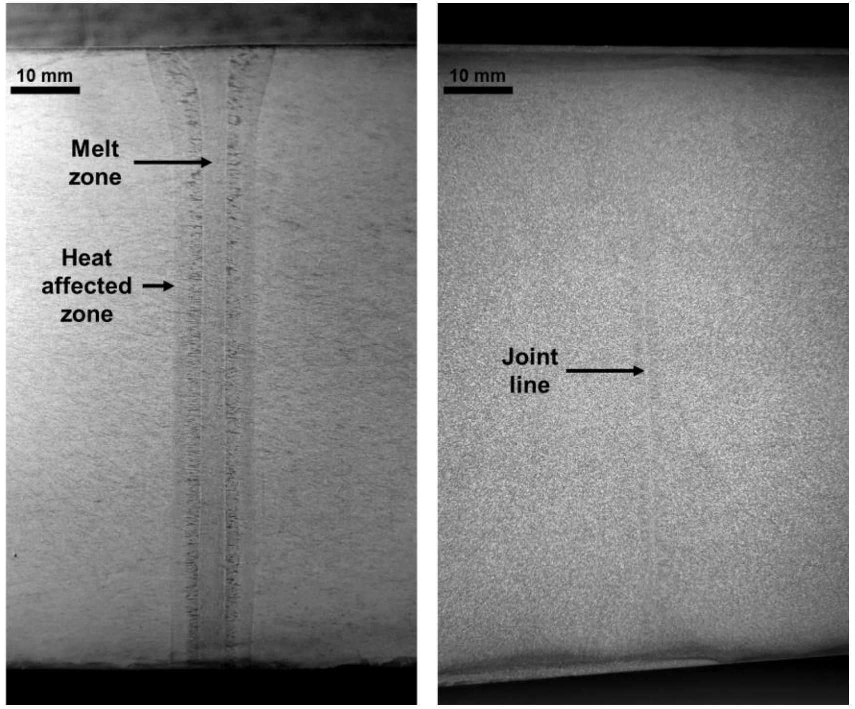
Summary of NDE Results

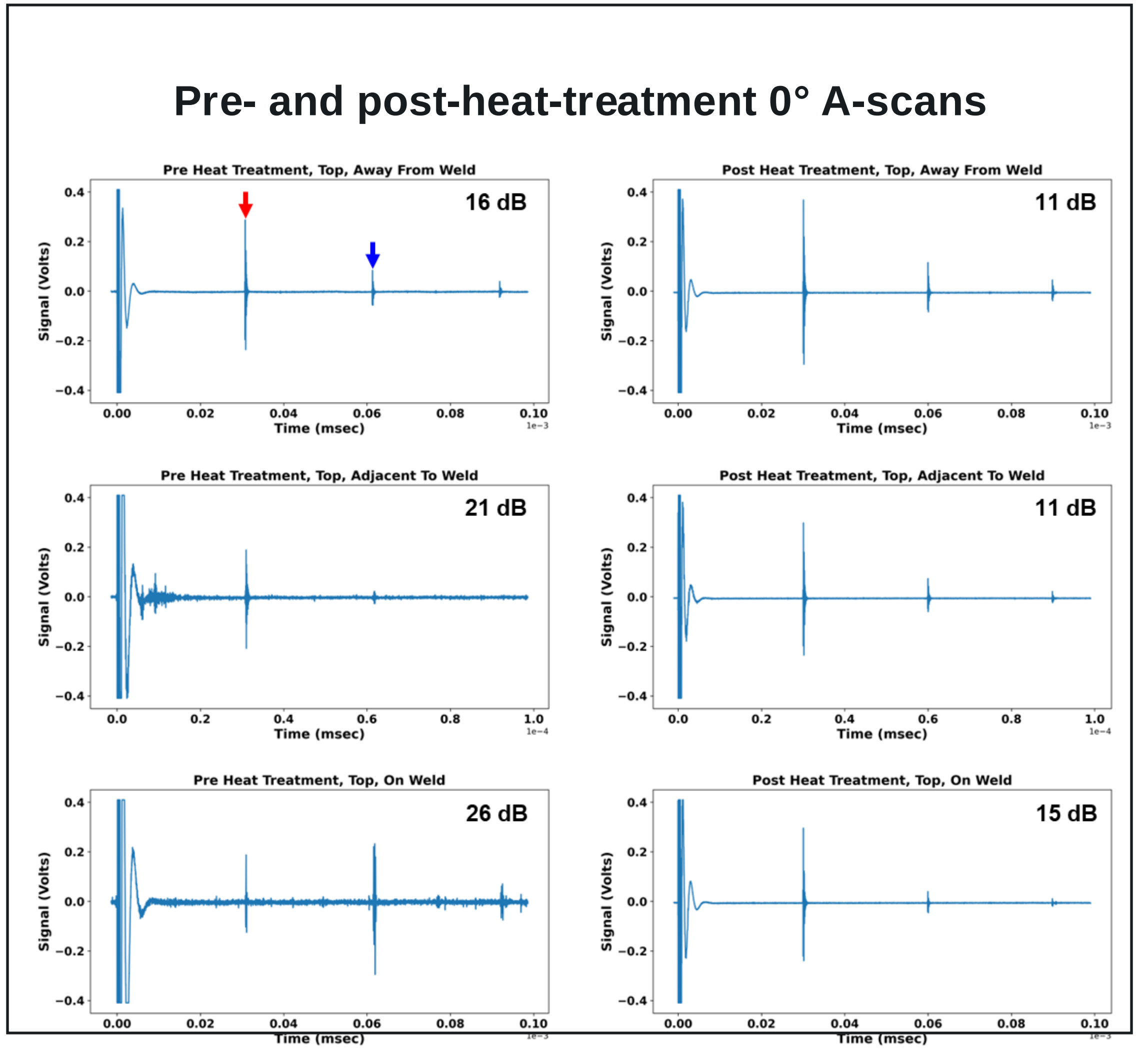
- Four EBW plates were made with simple square butt-welds. The plates were manufactured with different weld parameters
  - Ideal weld parameters (no defects)
  - Lack of fusion and keyhole defects
  - Large-scale lack of fusion defect
  - Lack of penetration defect
- PNNL examined the plates using multiple UT methods
  - FMC pulse-echo
  - TOFD pitch-catch
  - Tandem pitch-catch
- Data were presented at the January 2024 TIE meeting (ML24058A111)
- Of the UT methods tried, the TOFD approach was the most effective for defect detection and characterization
  - FMC and tandem showed LOF corner echoes but no depth information, and the LOP defect was not detected
  - TOFD showed different signal intensities from unfused versus fused regions, whereas there was virtually no difference between such regions using pulse-echo FMC or tandem
  - Depth sizing and length sizing of the weld defects was possible with TOFD
- Overall, the TOFD approach was the most effective for inspecting blocks made using EBW

How Does Heat Treatment Affect Inspectability?

- A section of mockup #1 (ideal weld parameters) was cut for heat treatment.
- Visual observation showed that the heat treatment changed the weld microstructure leaving a faint indication of the joint line.
- Pre- and post-heat-treatment 0° pulse-echo UT was performed.
- Results showed that the weld zone was less attenuative after heat treatment.
- Heat treatment was shown to improve ultrasonic transmission through the weld.

Pre **Post**

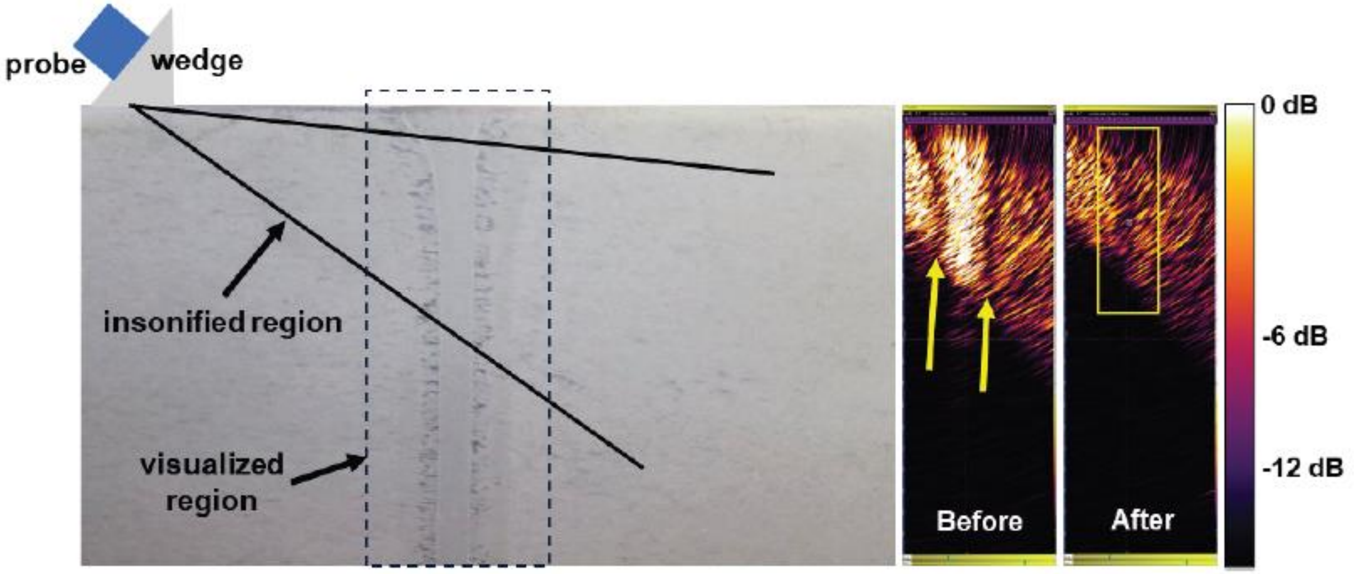




Pre (left) and post (right) heat treatment 0° A-scans taken away from the weld (top row), adjacent to the weld joint (middle row), and on the weld joint (bottom row). Attenuation measurements were made using the first two echoes (red and blue arrows; see the report).

Effect of Heat Treatment on FMC UT Images

- FMC scans were acquired at 10 MHz to investigate the weld ultrasonic signature before and after heat treatment.
- Prior to heat treatment, the microstructure resulted in shadows outlining the weld region (yellow arrows) and higher-intensity scatter within the weld region.
- Following heat treatment, the shadows were gone and the signal along the joint line was reduced.



FMC results before and after heat treatment. The yellow arrows indicate shadows observed along the outline of the weld region. The yellow box indicates the joint line region.

Next Steps

- Investigations into EBWs are complete.
- Next steps include evaluating inspectability of wire arc directed energy deposition (DED), also known as wire arc additive manufacturing (WAAM).
- PNNL has acquired 316LSi WAAM mockups and samples built by Lincoln Electric.
  - Sample plates and blocks (as built, not solution annealed)
  - Valve body mockups (on loan from EPRI)
    - ✓ One as-built
    - ✓ One surface conditioned
    - ✓ Both solution annealed

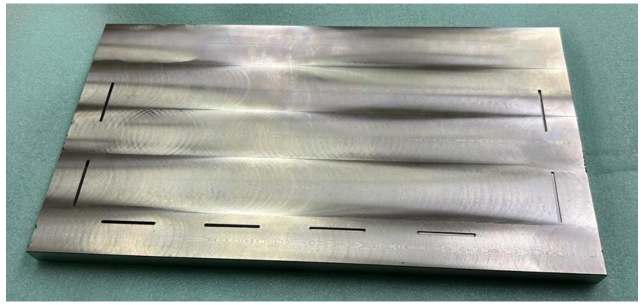
WAAM Samples and Mockups

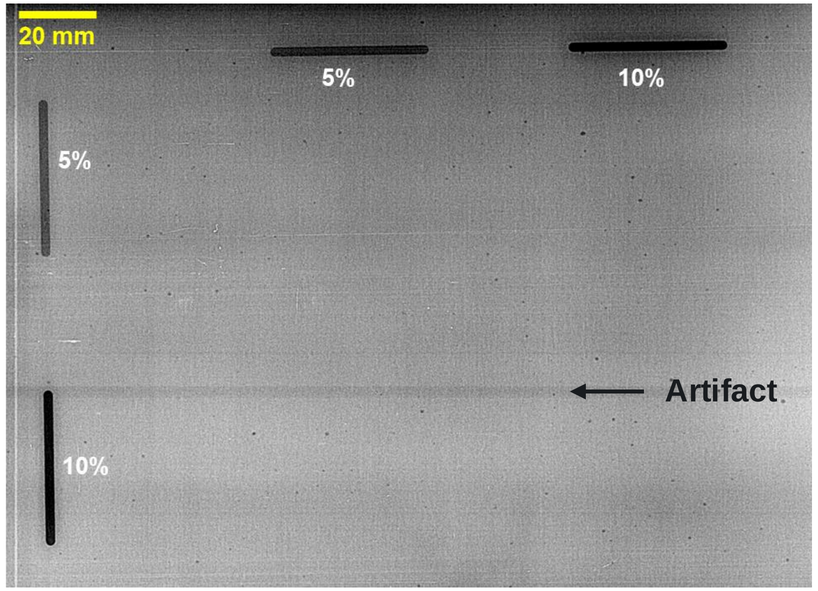
316 LSi Plate, ≈16 × 9 × 1 inch
Additional 316LSi, mild steel, and Inconel 625 samples were received from Lincoln Electric.

316 LSi valve bodies (up to ≈4 inch thick)
Both have been heat treated, one was surface finished. Both have had sections cut out to test mechanical properties (work done by EPRI).

Preliminary NDE Results

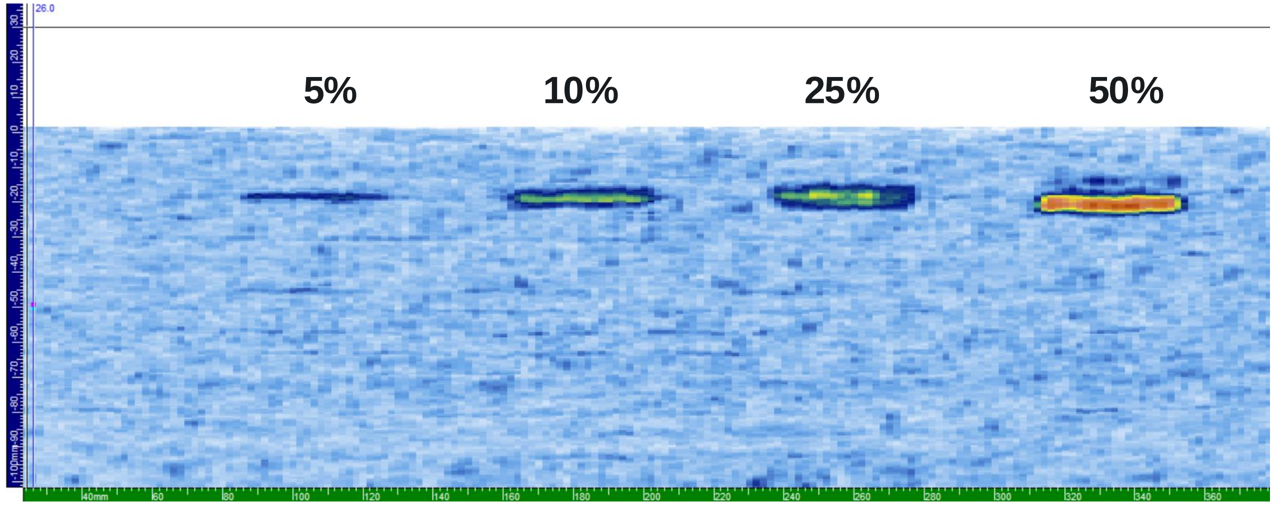
- The plate was machined smooth, and notch reflectors were added.
  - 5%, 10%, 25%, and 50% through-wall
  - Final plate thickness was 0.75 inch
- Radiography showed no defects and a very small volume fraction of porosities in the plate, as expected.
  - Typical porosities were <0.5 mm diameter
- Ultrasonic attenuation in the plate was extremely high for 316 stainless steel and comparable to attenuation in coarse-grained cast austenitic stainless steel.
  - Attenuation in the plate was about 10 times higher than attenuation in the valve body
  - Work will be done to determine if the difference is due to the solution anneal heat treatment
- UT showed that the notches were detected with direct echoes and L-waves.
  - Probes: 1 MHz and 2.25 MHz conventional pulse-echo (0.5 inch diameter, 45°, longitudinal and shear), and 2 MHz PA transmit-receive longitudinal (TRL) (10×5 elements)
  - All notches were detected with 2 MHz PA TRL
  - Notches were not readily detected with 2.25 MHz conventional shear
  - Notches were detected with 1 MHz conventional (longitudinal and shear), but signal-to-noise was low
  - No echo responses were seen with 1-V bounce (scan from the notch-side) using conventional or PA probes
  - Example images are shown on next slides



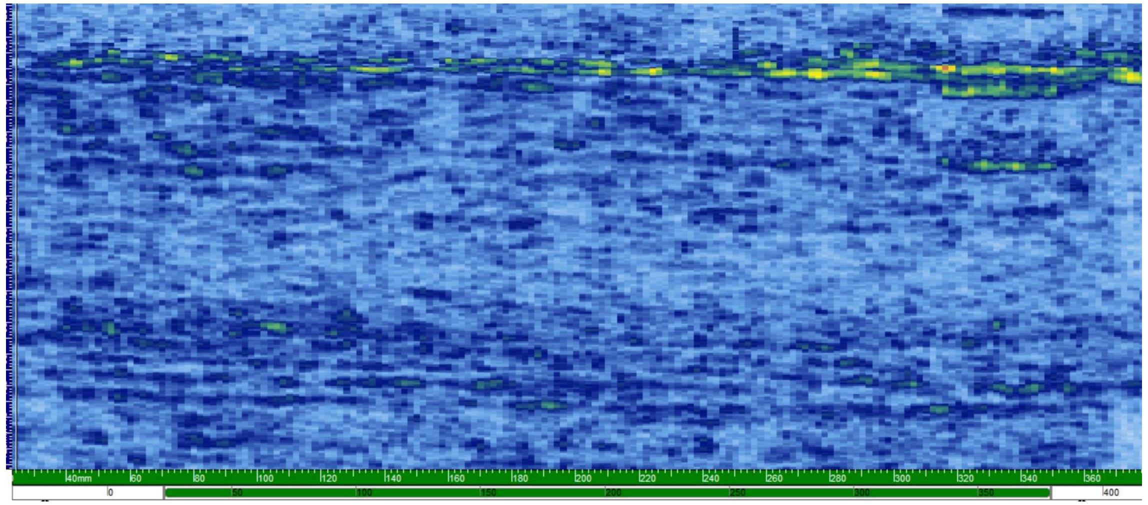


Radiograph

UT Example: 2 MHz PA

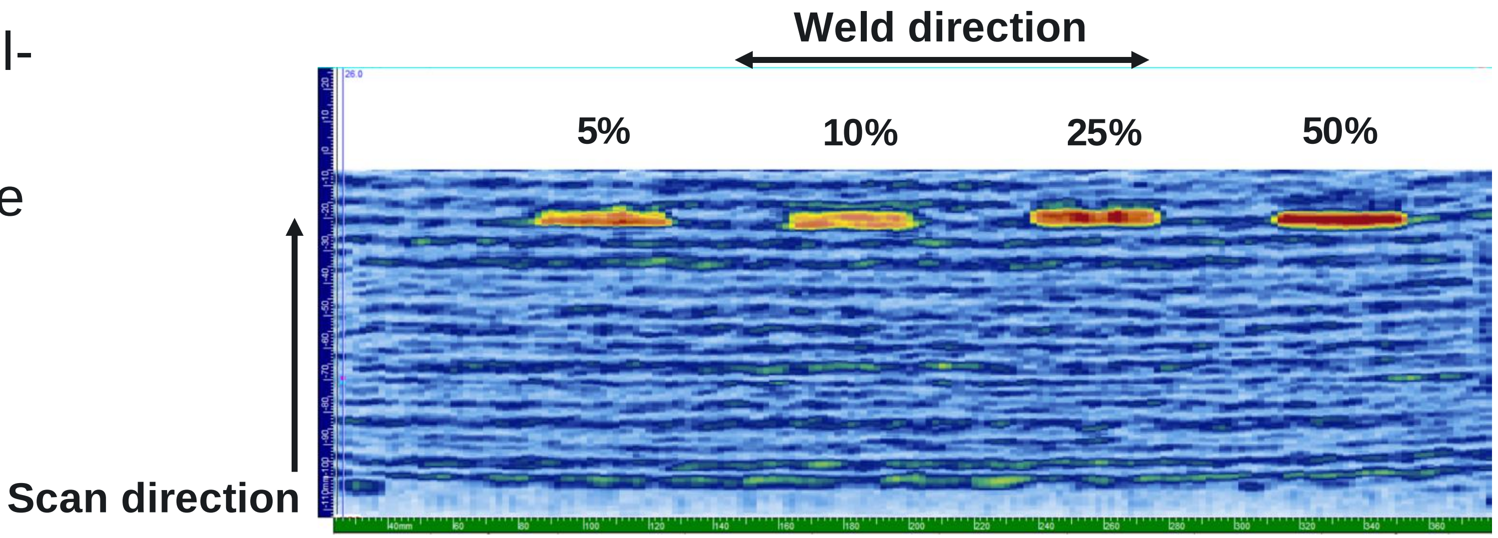


Scan from top of plate (1/2-V), 45°



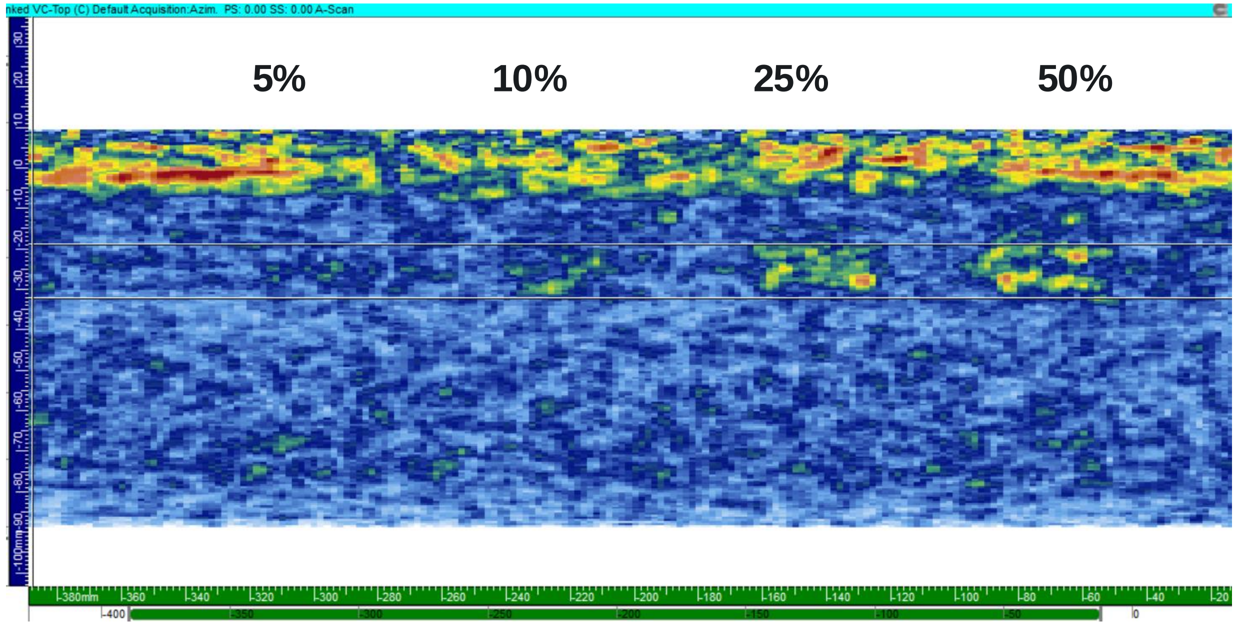
Scan from bottom of plate (full-V), 45°

- The notches were not clearly resolved in the full-V scans.
- Notch echoes observed from the top of the plate were often direct echoes from the notch tops and were not corner echoes.
- The weld pattern is apparent in the 30° scan even though the plate was machined smooth.

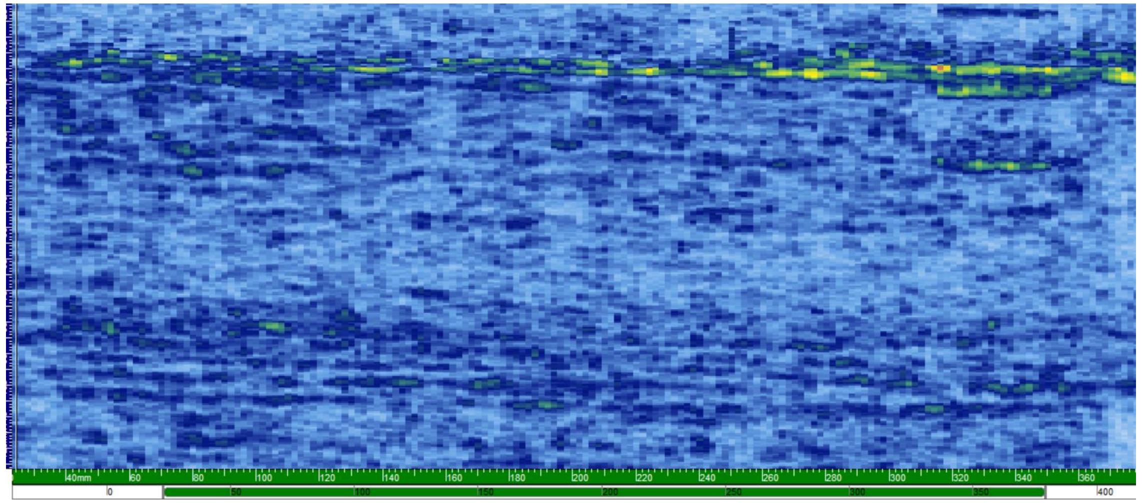


Scan from top of plate, 30°

UT Example: 2.25 MHz Conventional

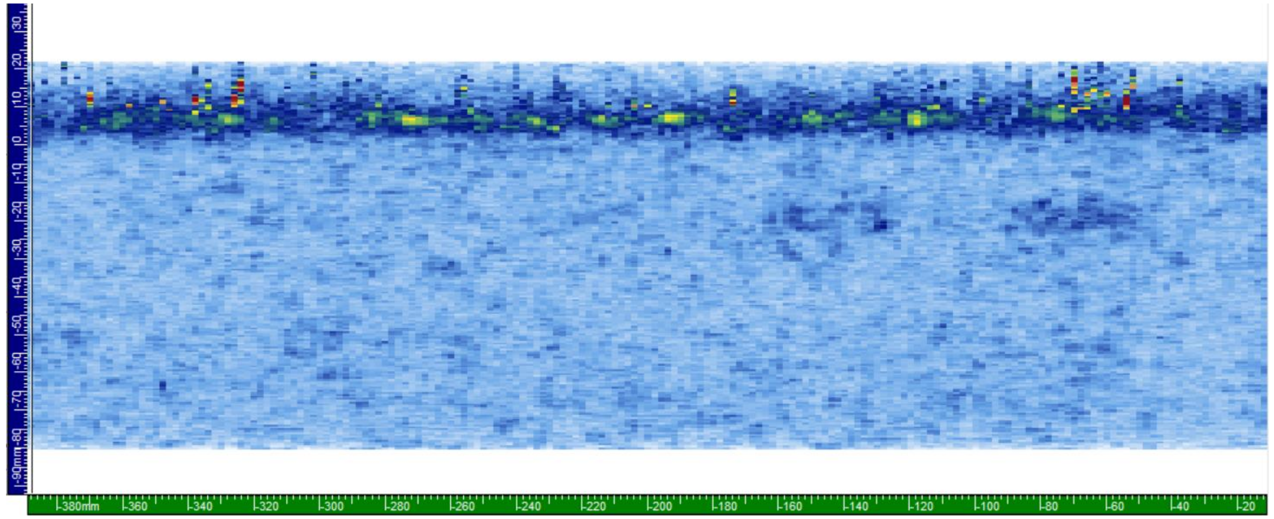


Scan from top of plate (1/2-V), longitudinal



Scan from bottom of plate (full-V), longitudinal

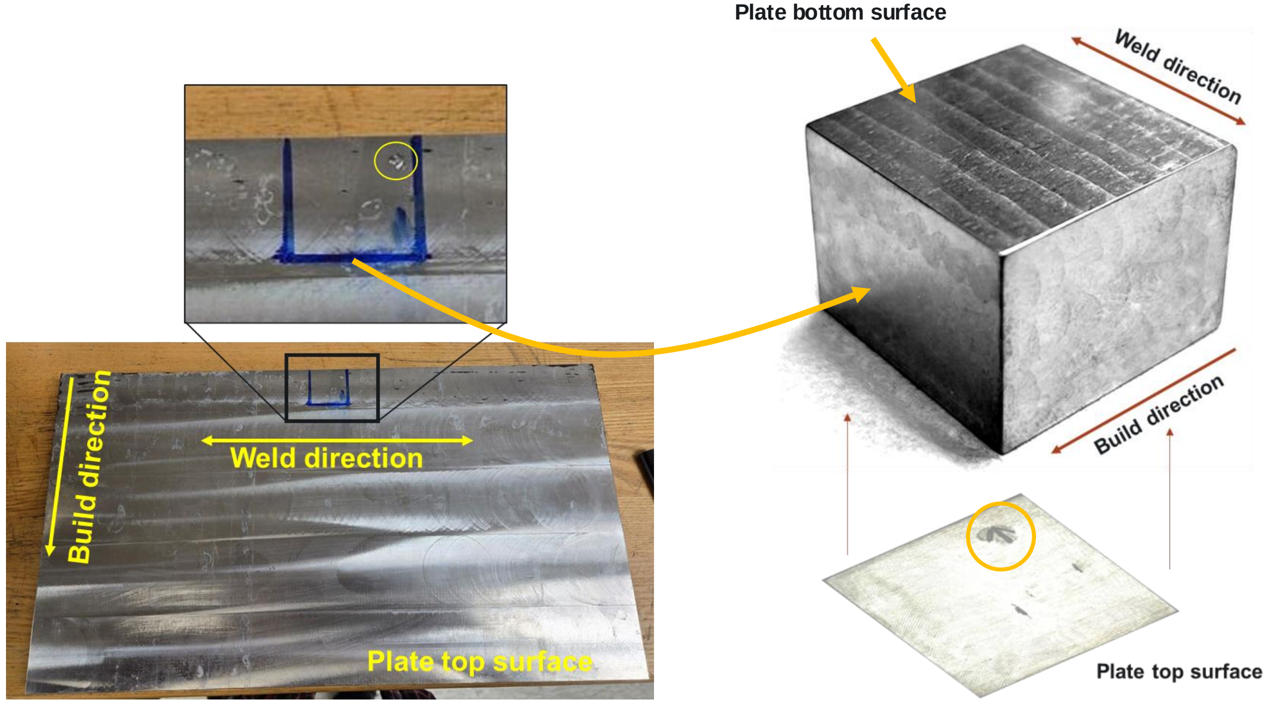
- The notches were not clearly resolved in the full-V or the shear scans.
- Notch echoes observed from the top of the plate were often direct echoes from the notch tops and were not corner echoes.

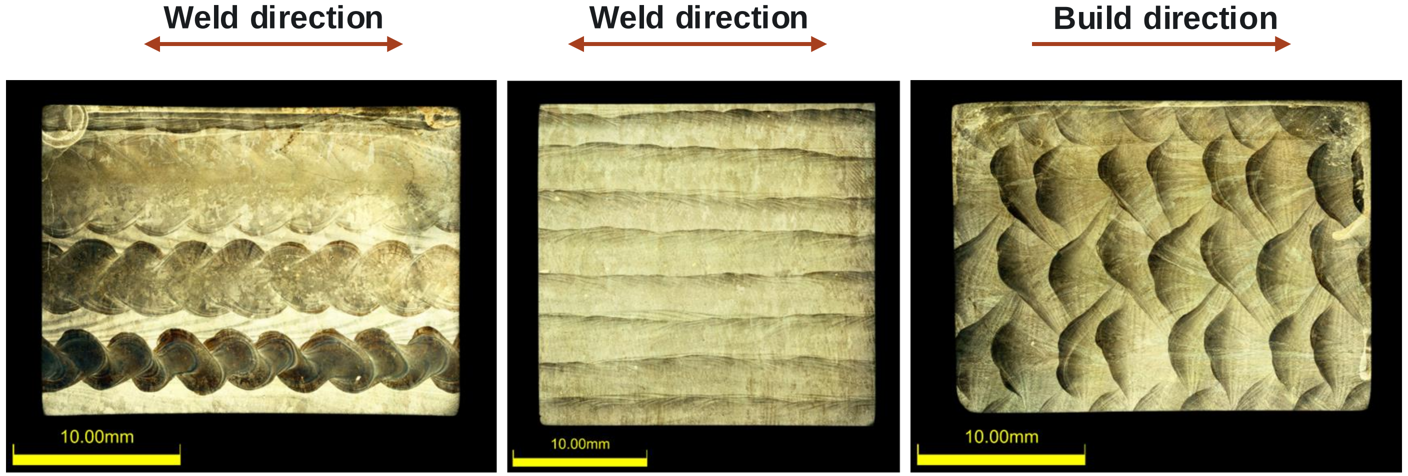


Scan from top of plate (1/2-V), shear

Plate Microstructure

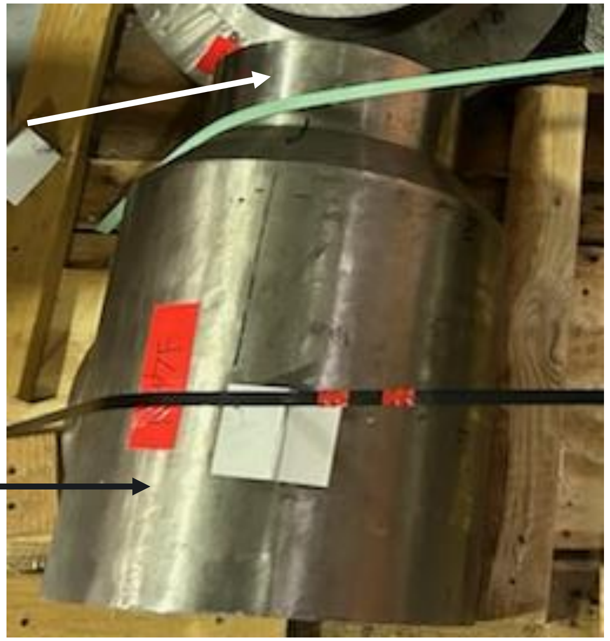
- A portion of the plate was cut for microstructural analysis.
- Three adjacent surfaces were polished and chemically etched.
- Results showed unique microstructure in each direction.
- No defects or porosities were noted.





Ongoing and Future Work

- Finish the analysis of the plate.
  - Complete the analysis of the UT data
  - Perform a solution-anneal heat treatment
  - Repeat UT scans to determine the effects of heat treatment on inspectability
  - Perform a second microstructural analysis
- Acquire PA data on the surface-finished valve body.
  - Circumferential and axial scans
  - Look at the thick and thin regions
  - Microstructural analysis
- Additional inspections on the valve bodies and plate sample are planned, but prioritization may depend on emerging results.
  - Determine the effects of different levels of surface finish on UT inspectability
  - Add cracks or notch reflectors to the valve body
  - Microstructural analysis of the valve body
- Technical Letter Report planned for 2026.



Thin region, ≈1.5 in. thick

Thick region, ≈4 in. thick

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Thank you