Impact of Deep Residual Stress on NDI Methods

21 September 2017

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Overview

- Summary of Current Knowledge
- Effect of Laser Peening on NDI of Fatigue Cracks in Aluminum Alloys
- Quantifying Ultrasonic “Dead Zone” in Cold Worked Holes
- Future Work

Acknowledgements

Dr. Adrian DeWald - Hill Engineering

Dr. Michael Hill - Hill Engineering

Dr. Mark Thomsen - A-10 ASIP Manager

Mr. Mark Bennett - Universal Technology Corporation

Mr. Brian Shivers – Southern Ohio Center for Higher Education

Summary of Current Knowledge

- Ultrasonic response from EDM and unloaded fatigue cracks differ by ~ 6dB for aluminum.
- Applied compressive stress reduces ultrasonic signal amplitude in aluminum by -6dB for every 4ksi for aluminum.
- **Applied compressive stresses** do not significantly affect BHEC or SECI on aluminum or titanium.
- Applied compressive stress affects fluorescent penetrant detection capability.
- CX of holes does not measurably affect BHEC on aluminum or titanium.
- CX of holes significantly affects SECI at the mandrel exit surface due to crack “tunneling”.

Summary of Current Knowledge (continued)

- CX of holes **reduces** ultrasonic detectability of fatigue cracks
  - Extent of ultrasonic dead zone not quantified or correlated to hole diameter or plate thickness.

- Deep residual stress surface treatments **do not** significantly affect SECI detectability in aluminum or titanium.

- Deep residual stress surface treatments significantly **affect** fluorescent penetrant detection capability.

What We Wanted to Know

(ERSI Workshop September 2016)

I. Quantify shear-wave ultrasonic detection capability for fatigue cracks propagating from CX holes.

- POD study for typical CX and no-CX countersink hole scenario
  - Semi-automated and manual scanning
- ***Develop model to address component geometry, plate thickness, hole diameter, % hole expansion, hole fill***
- ***Conduct empirical sensitivity studies to calibrate model***

II. Quantify effects of deep residual stress on crack closure and NDI of open surfaces.

- Ti-6-4 Beta peening study suggests compressive stress surrounding crack may be relieved, enabling penetrant to enter crack.
- ***Laser Peening study (Hill Engineering) should provide additional learning for Aluminum.***

Study Overview

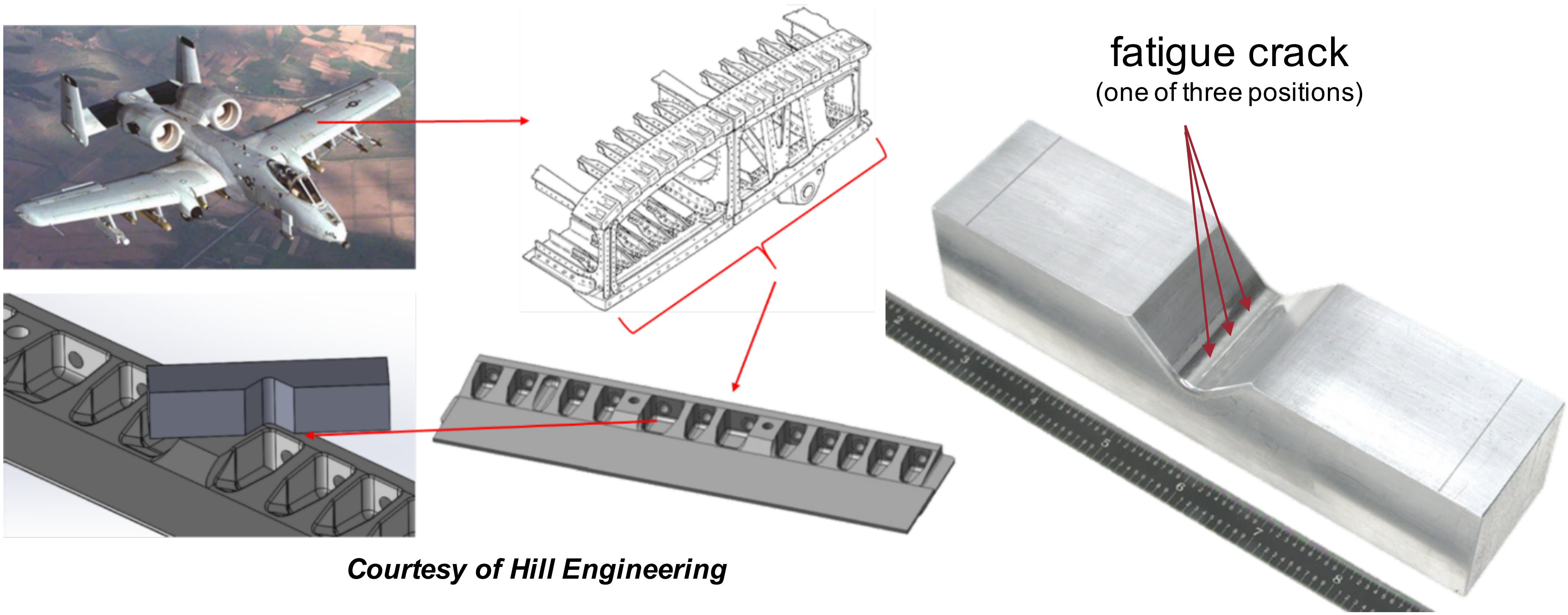
Objective

Quantify the effect of LSP on detectability of fatigue cracks in aluminum.

Approach

Measure and compare indication response on LSP treated and unpeened fatigue cracks specimens. Eddy current, fluorescent penetrant and ultrasonic methods evaluated.

7050-T7541 Specimen Configuration

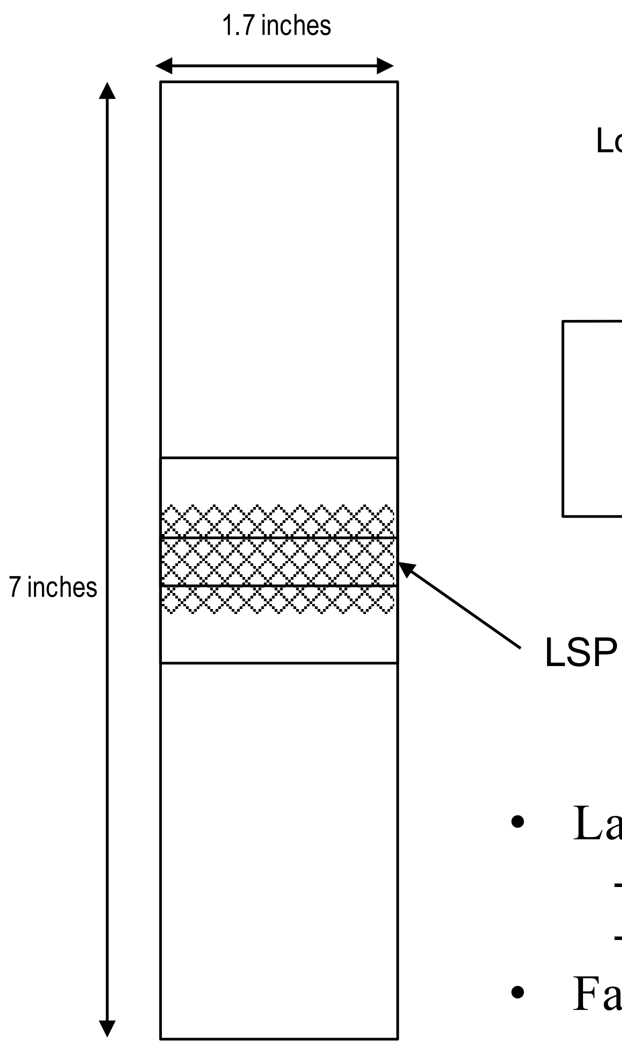


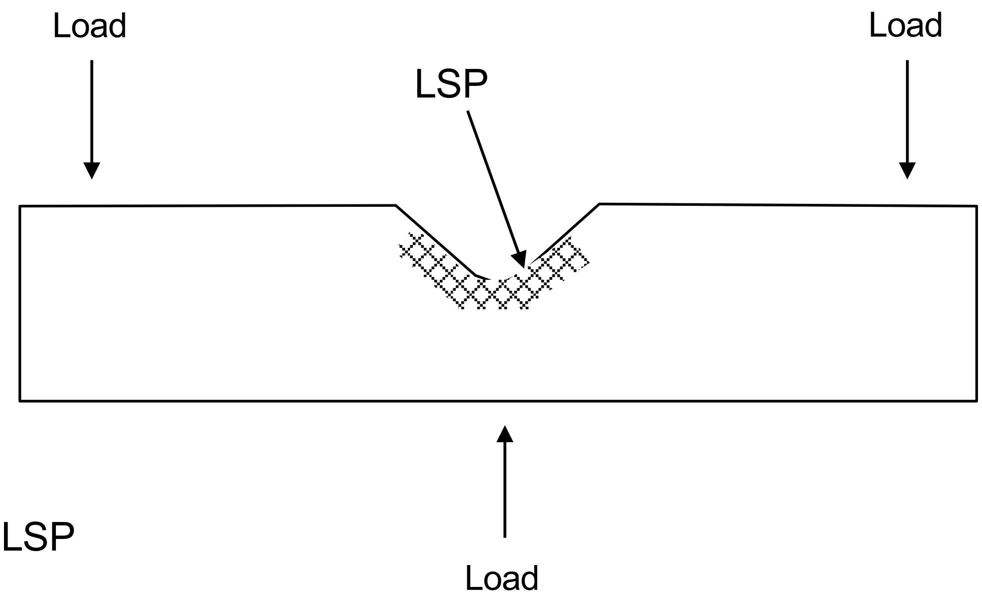
Courtesy of Hill Engineering

Fatigue Crack Specimens (***provided by Hill Engineering***)

- 20 ea. - Unpeened
- 20 ea. - LSP treated
- Precracked with 0.050 inch long x 0.025 inch deep electro-discharge machined (EDM) notches. EDM machined away then crack grown to target length.
- 0.070 inch – 0.300 inch target surface lengths

LSP Treatment

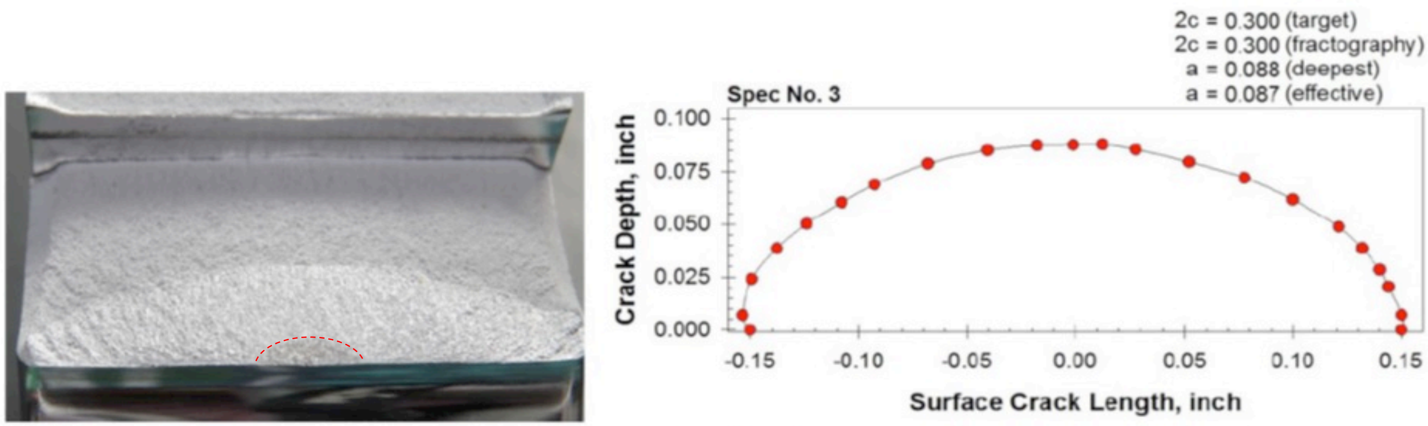




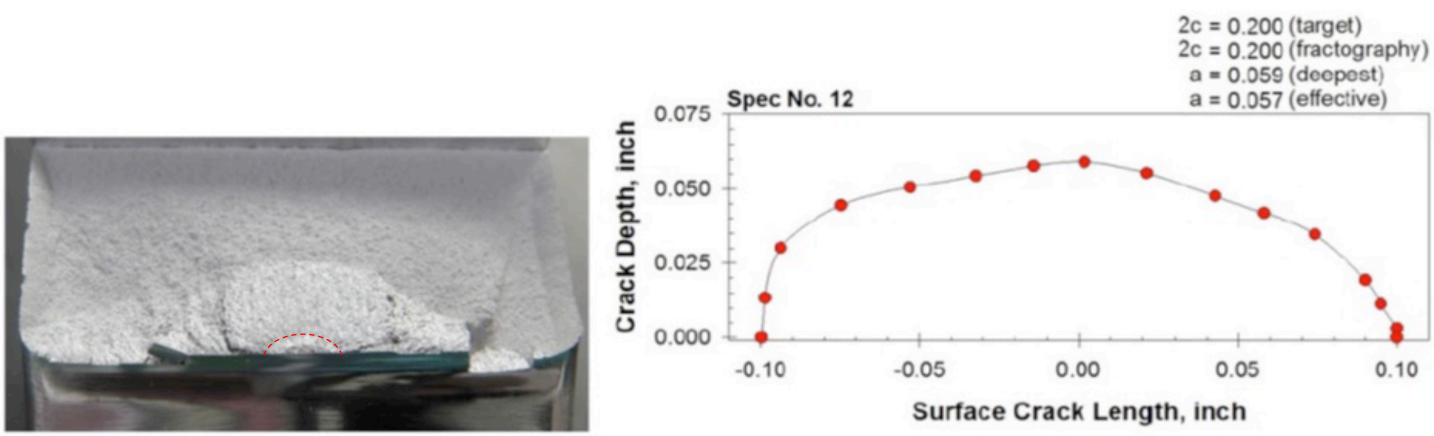
- Laser Shock Peen – Shaded Area
  - $4GW/cm^2$, 18ns – 3lyrs using aluminum tape ablative layer
  - 33% offset in two direction
- Fatigue cracks grown in 3-point bending.

Typical Aspect Ratios

Phase I Specimens



(a) Specimen No. 3

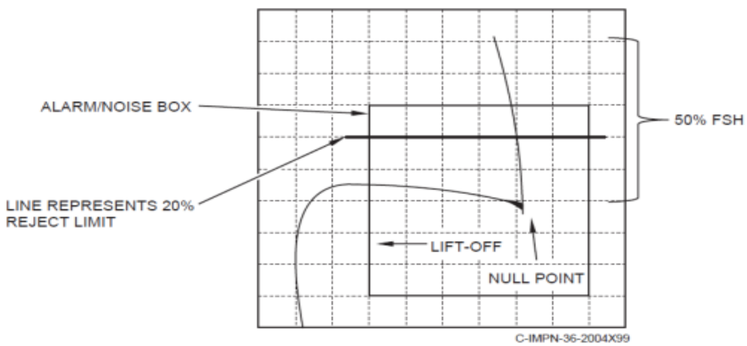


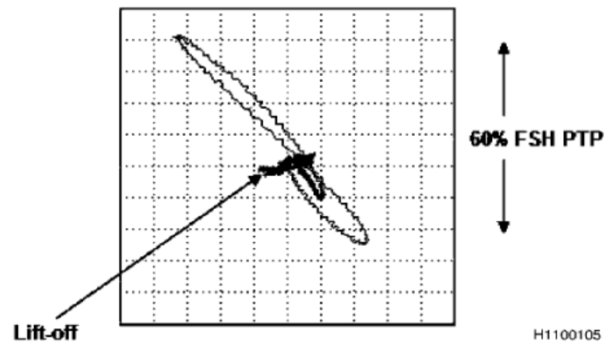
(b) Specimen No. 12

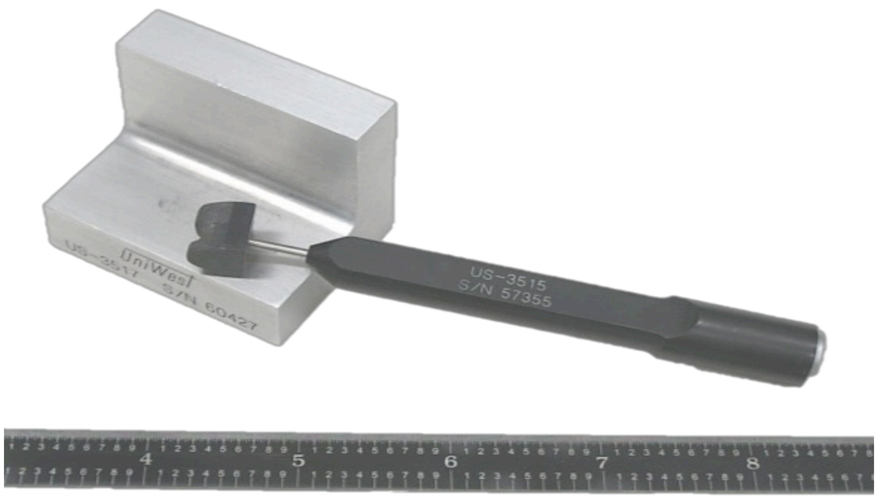
Courtesy of Hill Engineering

1.75 inch

Eddy Current Inspection Tools

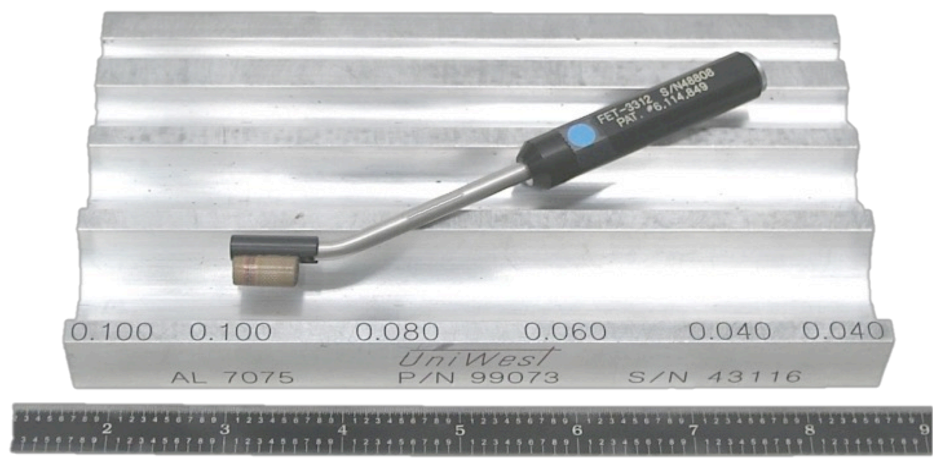






US-3515/3516 Probe

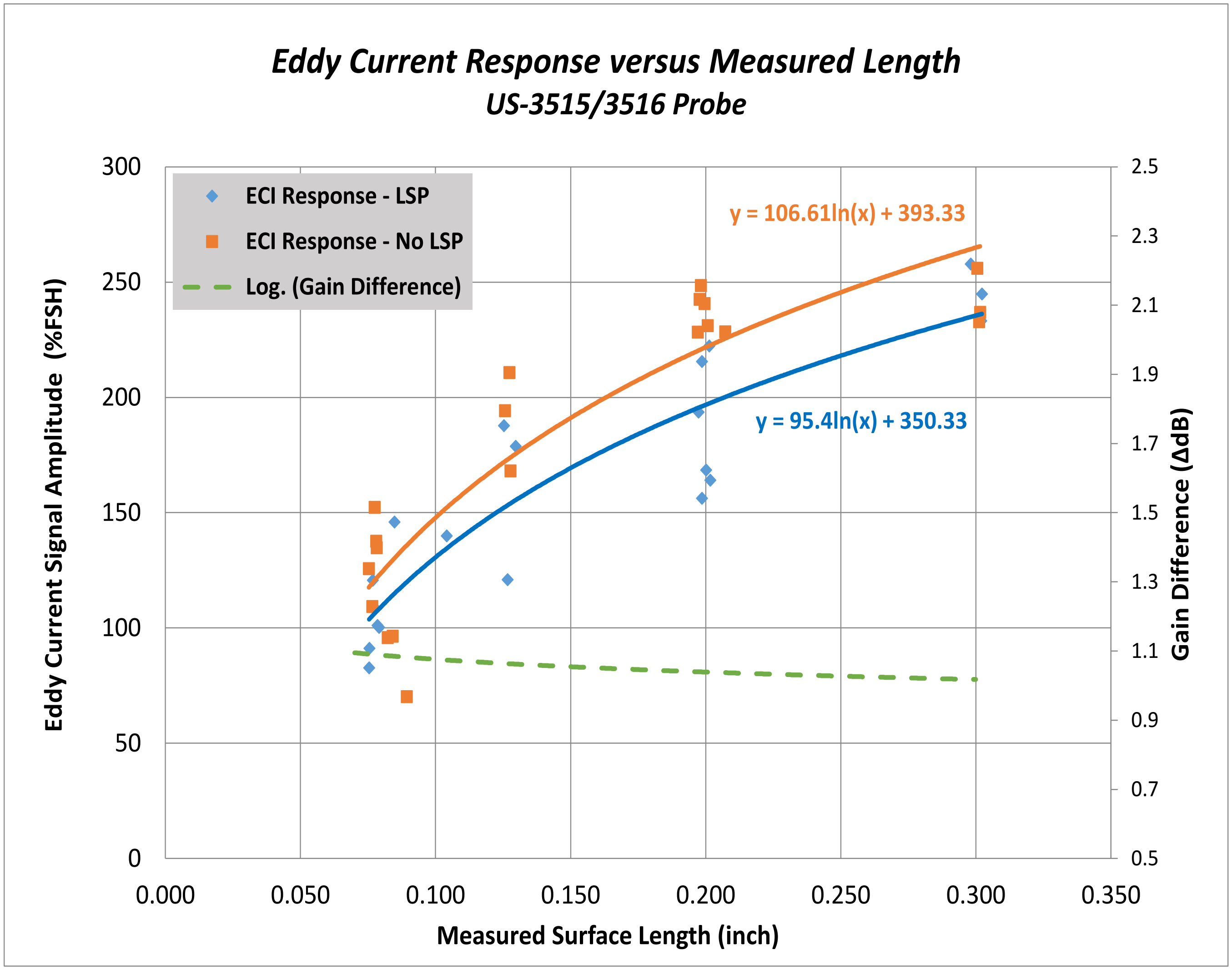
200 KHz



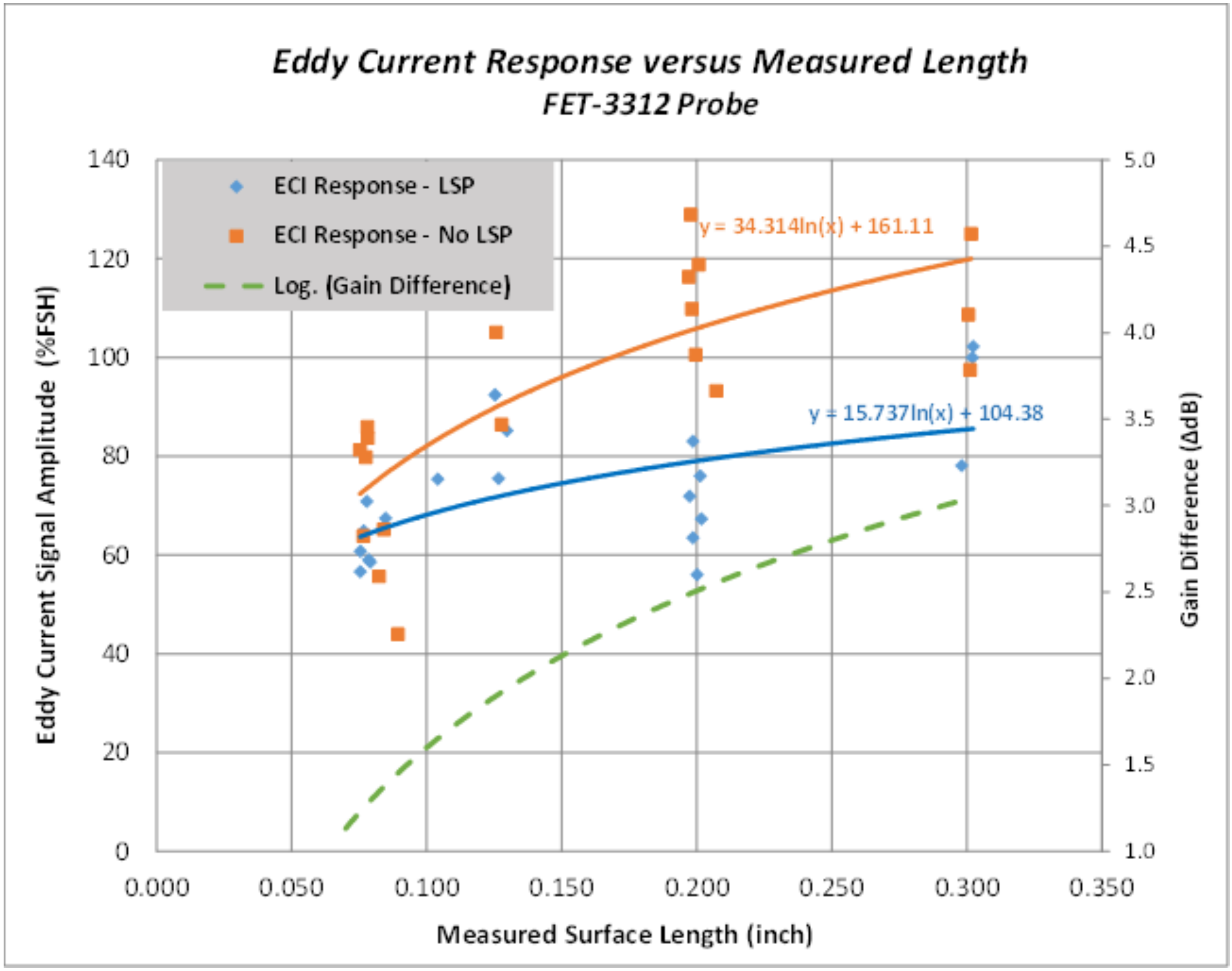
FET-3312 Probe

400 KHz

US-3515/3516 Probe Results



FET 3312 Probe Results



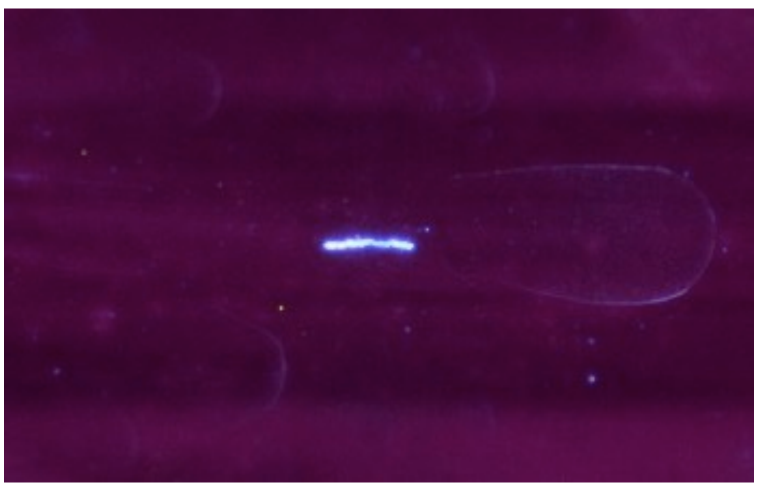
Calculation of FPI Indication Parameters using NIH Image J

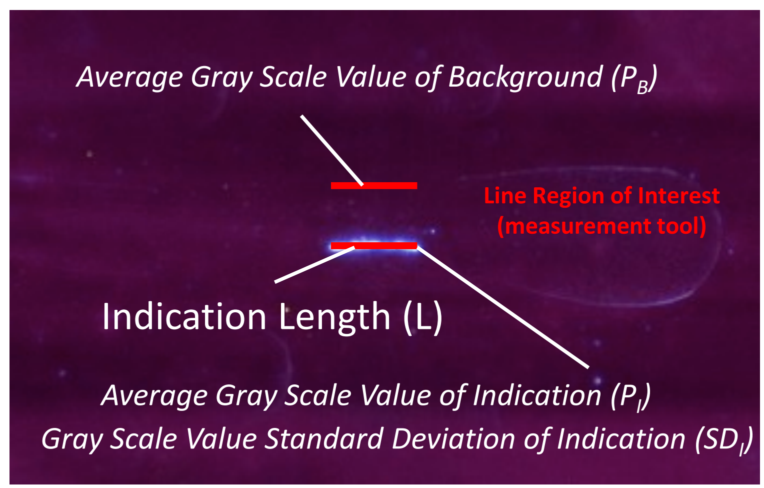
- Indication length (L)
- Average gray scale value along indication (PI)
- Standard deviation of gray scale value along indication (SDI)
- Background average gray scale value (PB)

Signal-to-noise (S:N) and factored length (LF) values were calculated and tabulated for each indication as follows:

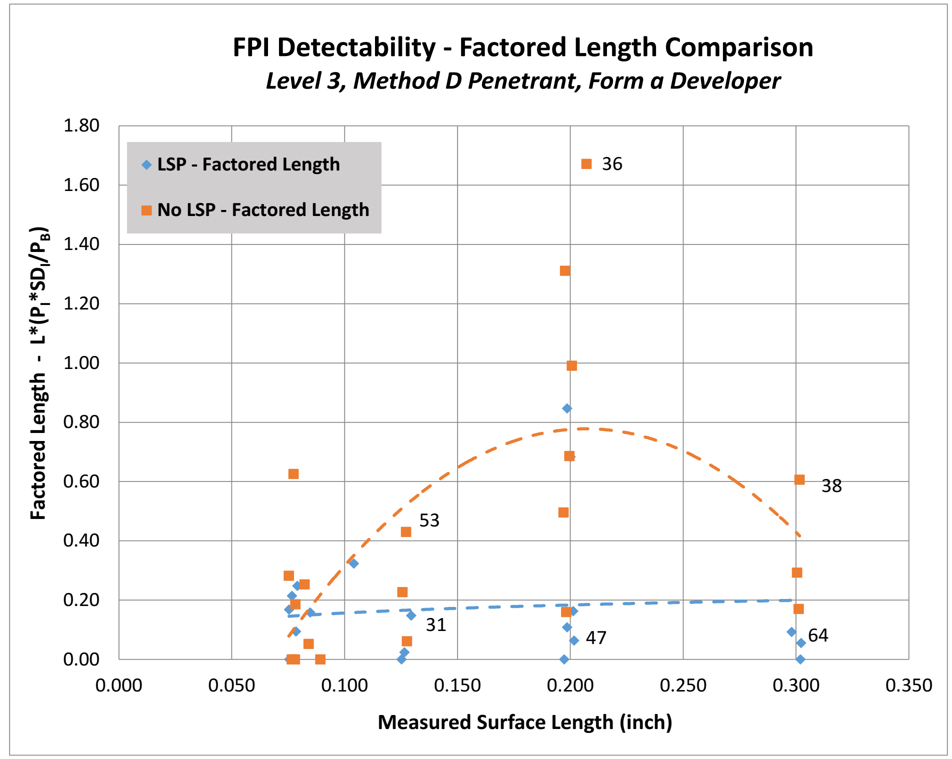
S:N = (PI – SDI)/PB *Equation 2*

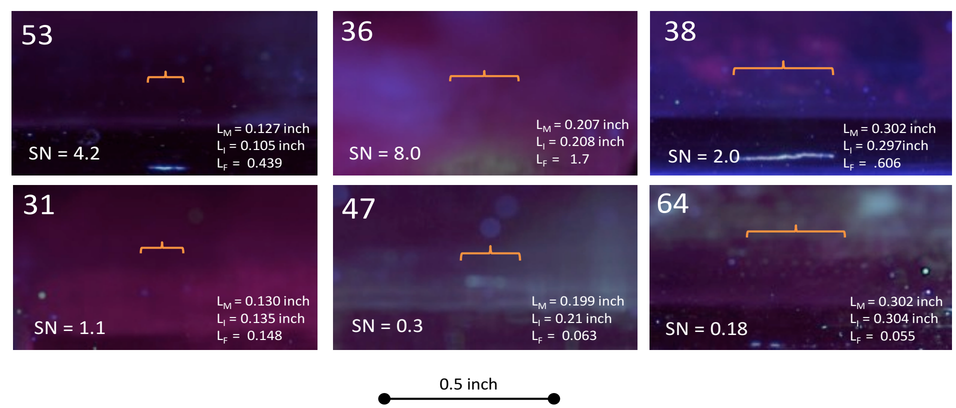
Factored Length (LF) = L * S:N *Equation 3*





Level 3 FPI Process

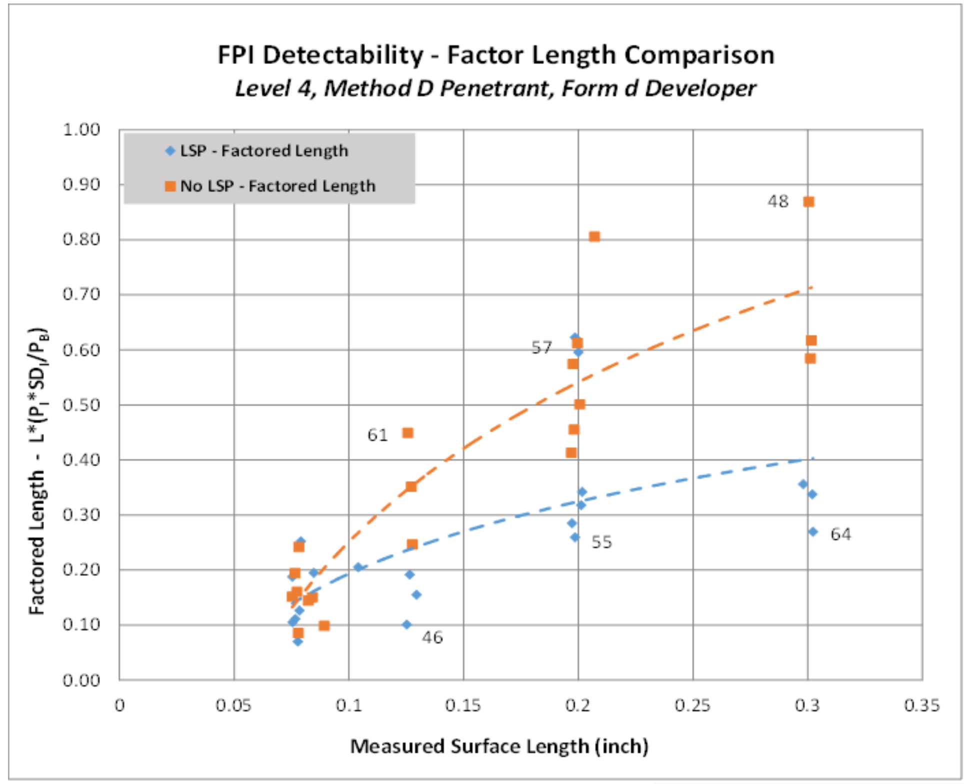


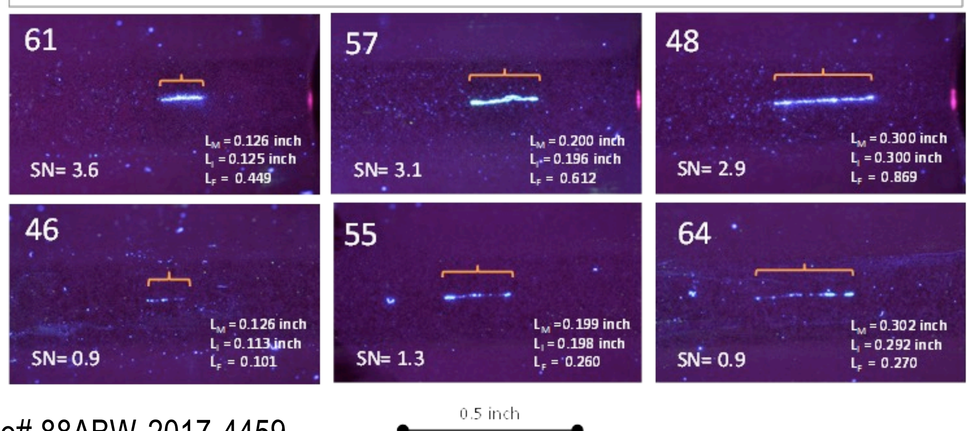


<u>Level 3 FPI Process</u>

- Level 3 (high sensitivity penetrant)
- 30 minute penetrant dwell
- Method D (5% spray remover)
- Form a – dry powder developer
- 10 minute developer dwell

Level 4 FPI Process

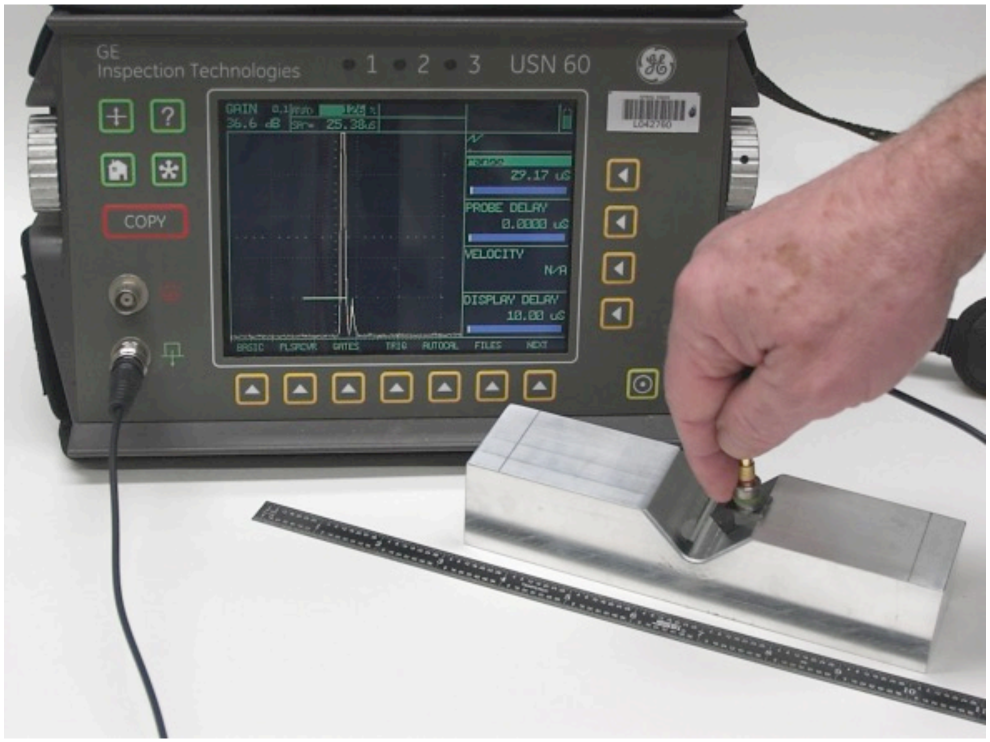


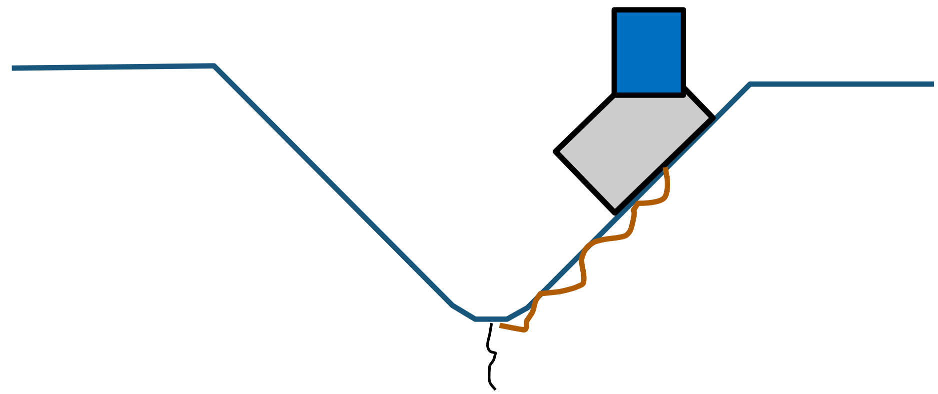


<u>Level 4 FPI Process</u>

- Level 4 (ultrahigh sensitivity penetrant)
- 30 minute penetrant dwell
- Method D (5% spray remover)
- Form d – nonaqueous developer
- 15 minute developer dwell

Surface Wave Ultrasonics





<u>Surface Wave Unit</u>

90° shear wedge

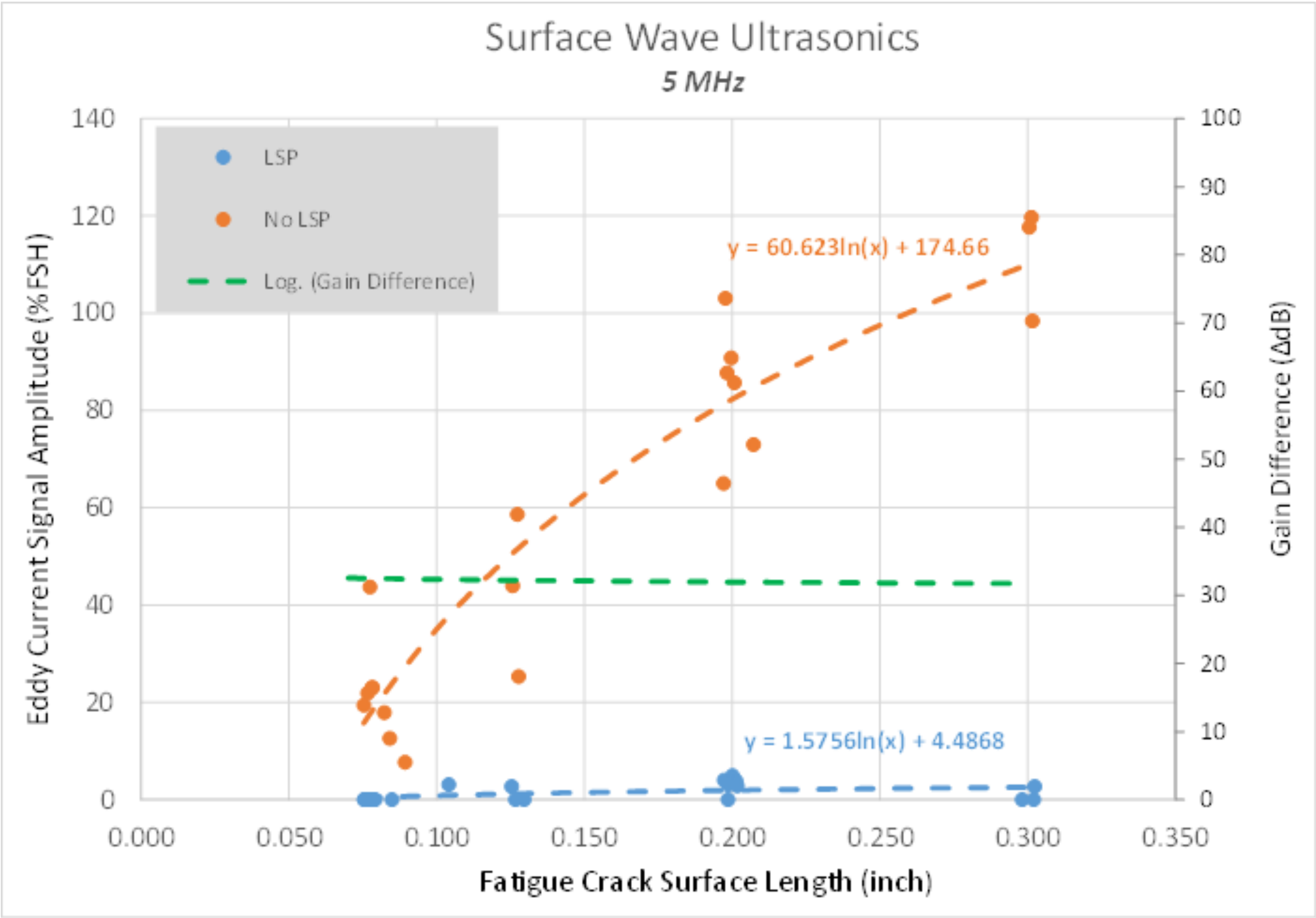
10 MHz, 0.25 inch diameter transducer

<u>Calibration</u>

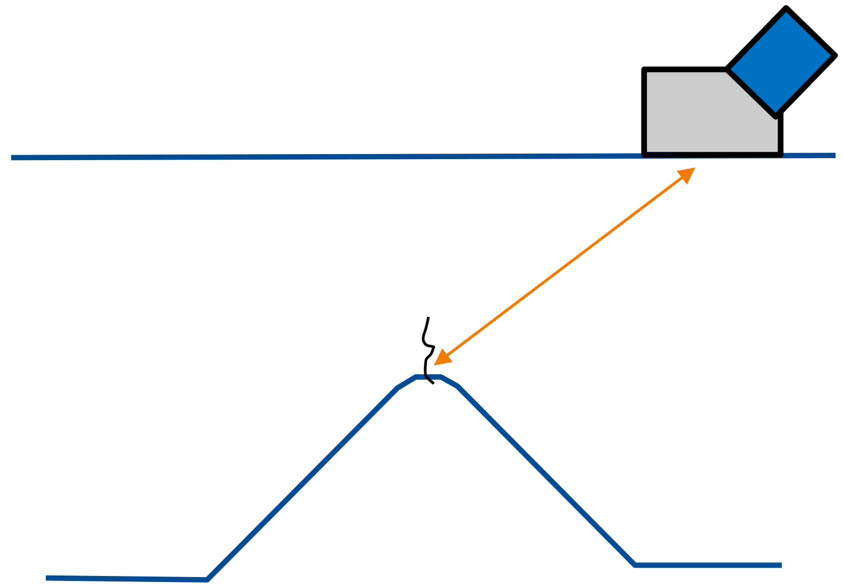
80%FSH from 0.02 x 0.01 inch notch

in a 7075-T7 reference plate

Surface Wave Ultrasonics Results



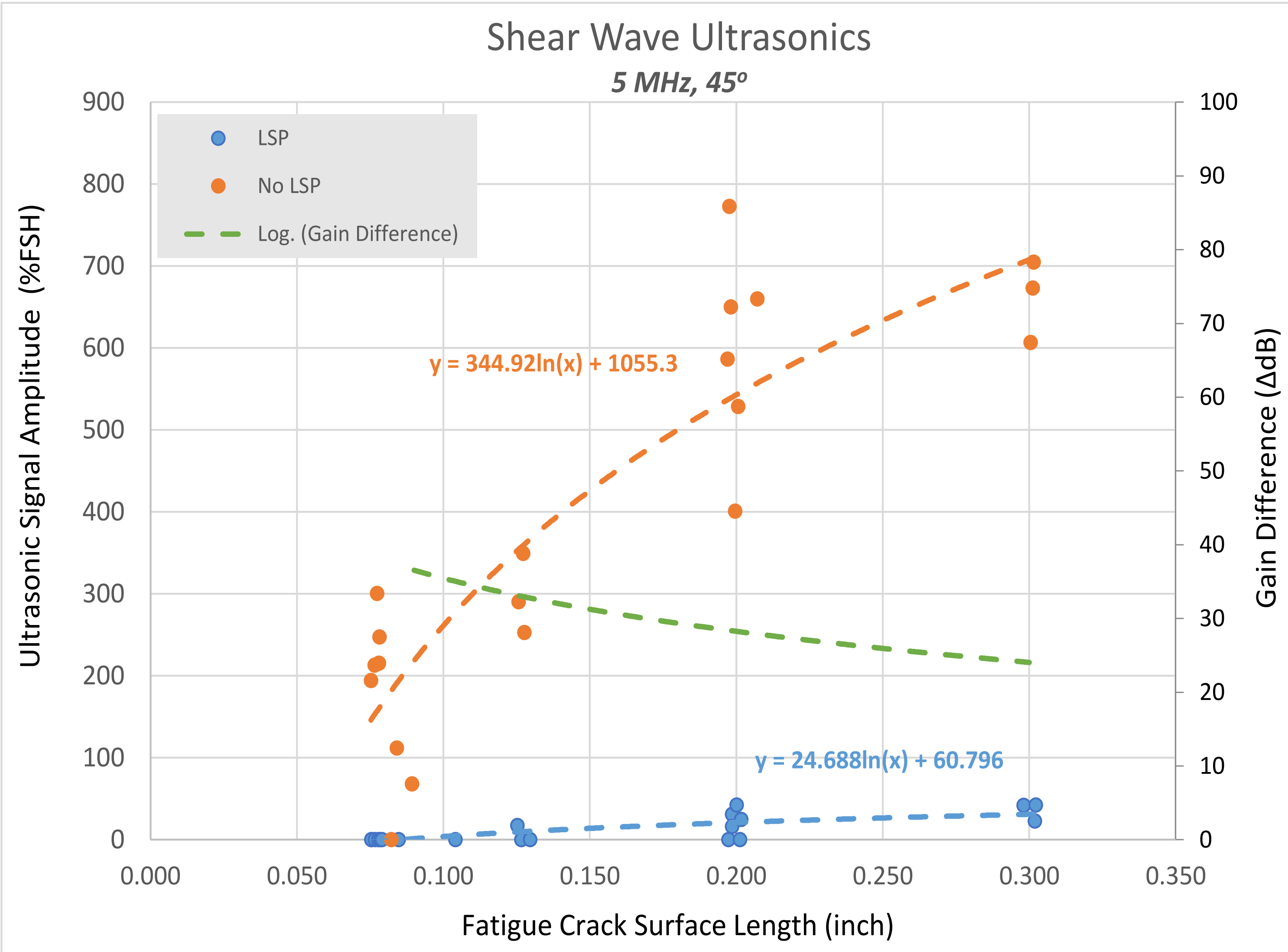
Shear-Wave Ultrasonics



Surface Wave Unit
45° shear wedge
10 MHz, 0.25 inch diameter transducer

Calibration
80%FSH from 0.02 x 0.01 inch notch
in a 7075-T7 reference plate

Shear-Wave Ultrasonics Results



Conclusions – LSP Effects

- LSP reduced ECI response from fatigue cracks by up to 1dB when the US-3515/3516 probe was used.
- LSP reduced ECI response from fatigue cracks by up to 3dB when the FET-3312 probe was used.
- Fluorescent penetrant detectability significantly degraded as a result of residual compressive loads imparted by LSP applied to 7050-T7541 aluminum.
- A combination of Level 4 (ultra-high sensitivity) fluorescent penetrant and focused eddy current will provide optimum detection capability.
- Surface and shear wave ultrasonics are not viable techniques to detect fatigue cracks in LSP aluminum surfaces. Ultrasonic responses from fatigue cracks were reduce by >26dB on LSP treated surfaces.

Quantifying Ultrasonic Dead Zone in Cold Worked Holes - Study Overview

Objective

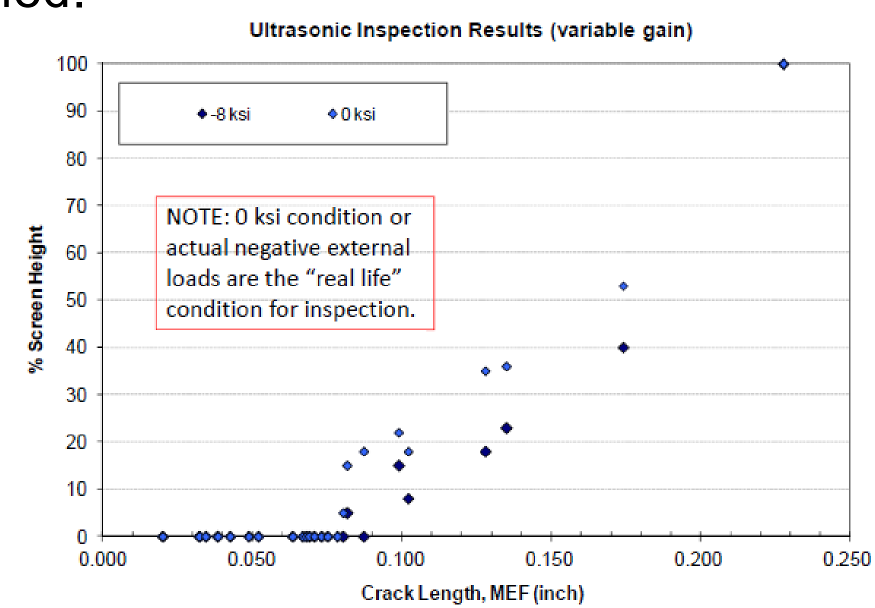
Quantify extent of "ultrasonic dead zone" extending from hold worked holes.
Establish correlations to hole diameter and/or plate thickness.

Approach

Measure, map and compare ultrasonic response of fatigue cracks extending from cold worked holes in various hole diameters and plate thicknesses.

Quantifying Ultrasonic Dead Zone in Cold Worked Holes - Study Overview

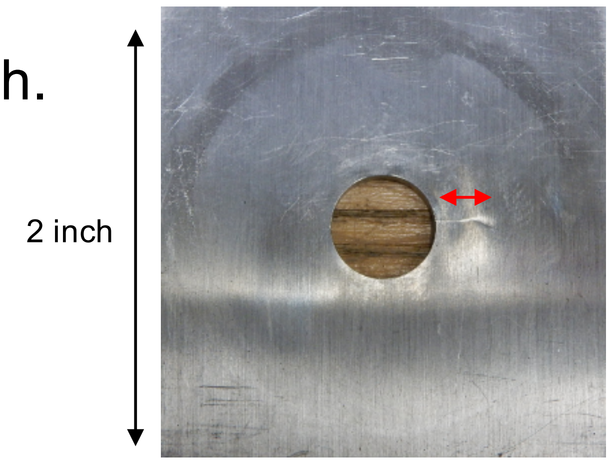
- CX of holes **reduces** ultrasonic detectability of fatigue cracks
- Crack must extend beyond compressive zone to be detectable by UT
- Previous efforts suggest compressive stress zone extended >0.075 inch beyond edge of hole for the scenario investigated by Forsythe and Mills.
- Correlation between hole diameter, plate thickness and compressive stress zone (i.e. ultrasonic dead zone) not well defined.
- Characterization of this effect is critical to:
  - Optimizing inspection techniques
  - Estimating UT detection capability

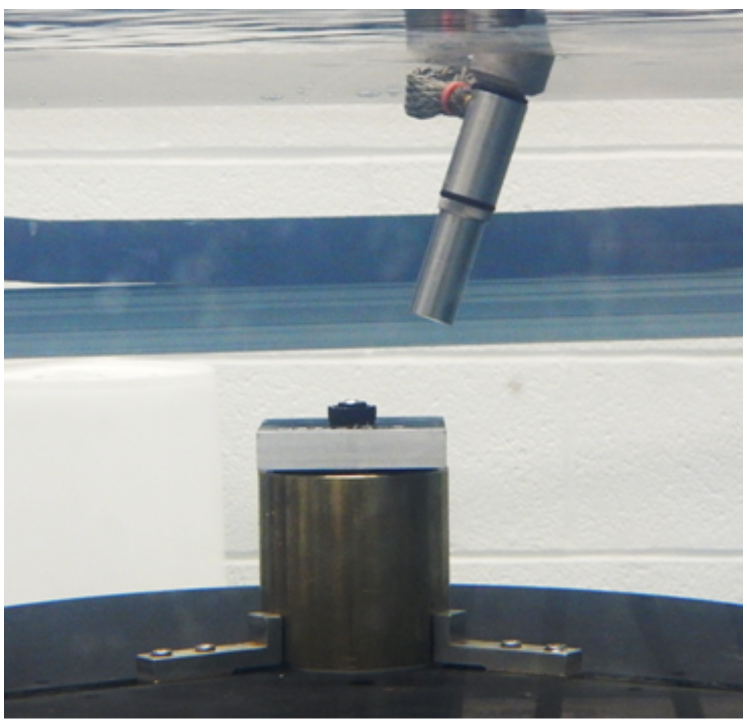


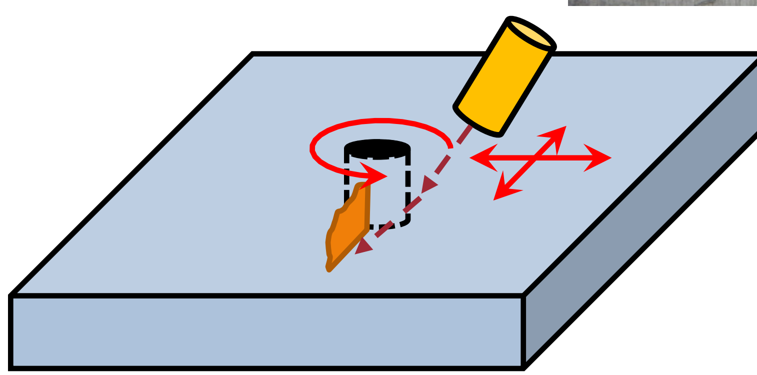
Forsythe, D., Mills, T. "Results of Study of Applied Stress and CX Process on Detectability of Fatigue Cracks"

Measurement Approach

- Map ultrasonic response along cracks grown in CX holes.
- Characterize “dead zone” for a range of hole diameters and plate thicknesses
  - Plate thicknesses: 0.100, 0.508 inch
  - Hole diameters: 0.280 inch, 0.450 inch, 0.540 inch
- Highly focused ultrasonic immersion inspection ≈ 0.020 inch focal spot
  - 45 degree shear, 10 MHz
- Map reflected ultrasonic energy along crack length.

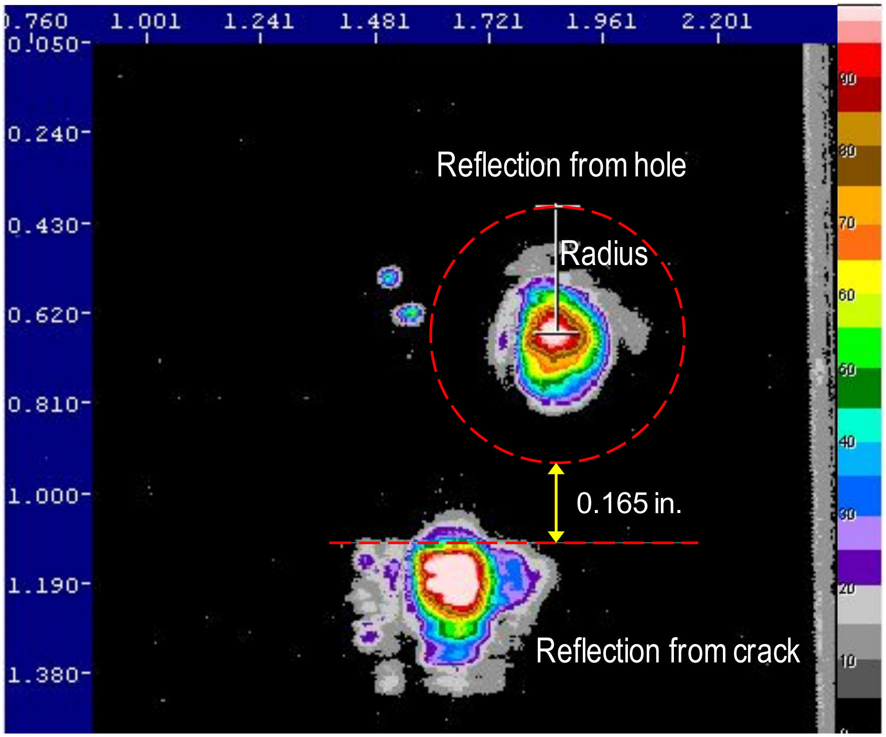






Ultrasonic C-scan Results

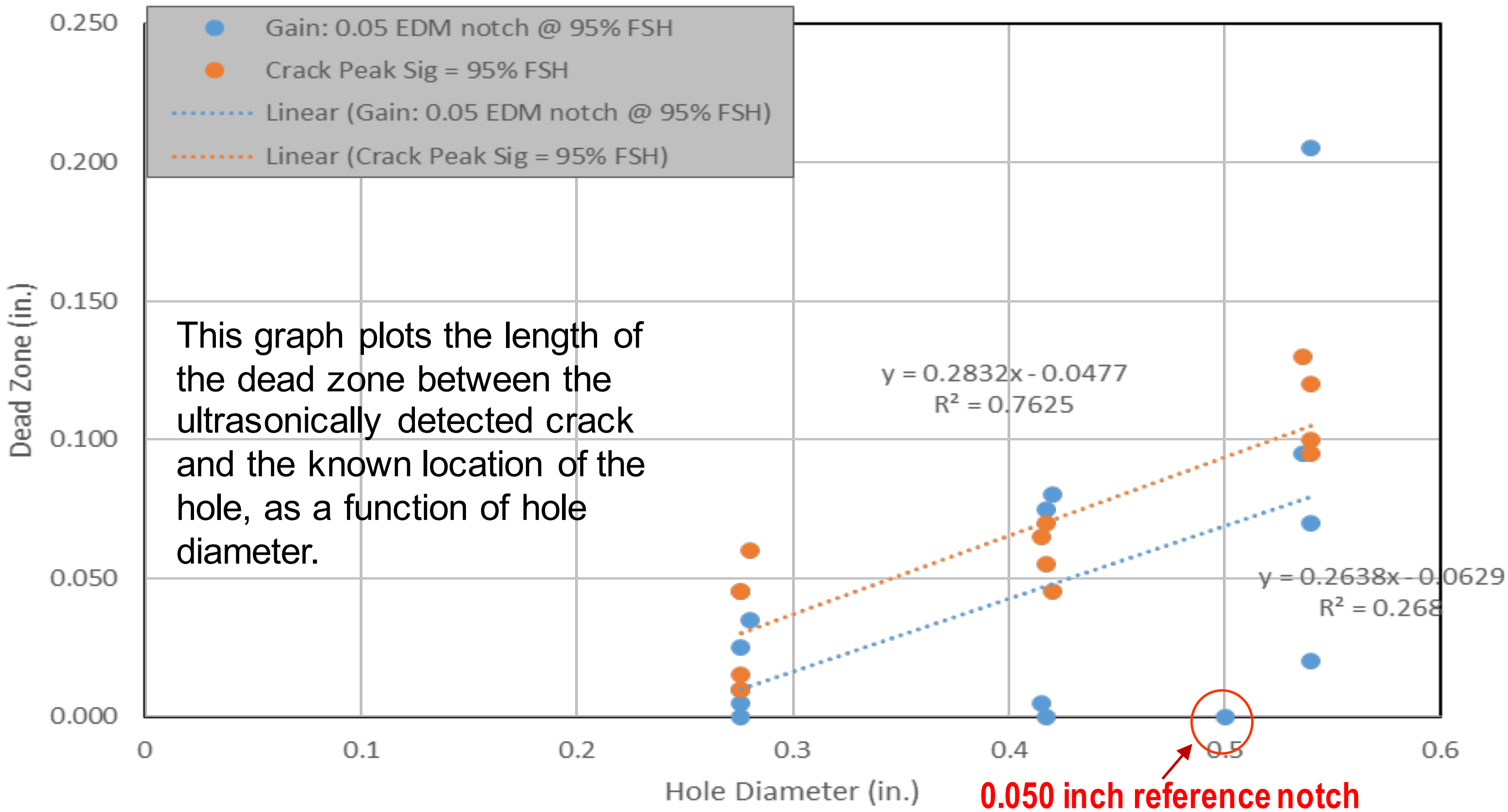
- Twelve fatigue crack specimens tested.
- The ultrasonic data were acquired by raster-scanning across the fatigue crack in 0.005” steps.
- Each ultrasonic “C-scan” contained an image of the hole as well as the crack.
- No reflection between the hole radius and the crack signal suggests the cold work suppresses a reflection from the crack.



In this C-scan image the crack signal begins 0.165 inches away from the hole. In this “dead zone” no ultrasound is reflected from the crack.

- 6dB drop defines edge of crack response.
- Dead zone measured twice:
  1) Reference gain set at peak response (95% screen height) from fatigue crack.
  2) Reference gain set at 95% screen height response from 0.050 inch corner EDM notch in 0.540 inch D hole, 0.508 inch thick sample.

Data Analysis



- The "dead zone" around each hole found to be proportional to the diameter of the hole **with significant scatter**.
- Similar analysis showed no dependence of the dead zone on thickness.

Conclusions – Cold Worked Holes

- Extent of ultrasonic dead zone correlates to hole diameter.
- No correlation to plate thickness observed.
- Significant scatter suggests variability in compressive stress profiles, crack morphology or closure.
- **Use upper bound of UT dead zone estimates to correct UT POD estimates for cold worked hole scenarios.**
- **Ultrasonic inspections of cold worked holes must be designed to interrogate beyond the tangency of the hole.**

Future Work
What We Still Wanted to Know

I. **Quantify UT dead zone in Cx holes**
   - Investigate cause of dead zone variability
   - Size UT dead zone for a range of Cx levels
   - Correlate UT dead zone to residual stress and fastener camera measurements
   - Define optimum UT system design for Cx holes
   - Develop Cx correction factors for UT POD estimates

II. **Investigate the impact of fastener installation on ultrasonic fatigue crack detectability?**
   - Taper-Lok fasteners
   - Interference fit fasteners
   - Interference fit fasteners installed in cold worked holes.

III. **Investigate the impact of deep residual stress treatments on fatigue crack detection capability?**
   - Laser shock peening on titanium alloys
   - Shot peening – aluminum and titanium (UT and FPI focus)

Questions?