Air Force Research Laboratory

Impact of Deep Residual Stress on NDI Methods

Engineering Residual Stress Implementation Workshop

15 September 2016

John Brausch
Materials Integrity Branch
Systems Support Division
Materials and Manufacturing Directorate

Integrity ★ Service ★ Excellence

Questions to Answer (v2)

A Century of Scientific Excellence

1. What role does Non-Destructive Inspection play within your role of managing airframe structure?

2. What guiding documents define the role of NDI within your organization?

3. Do you see the need to make any changes or updates to the NDI techniques used to find "damage" within a deep residual stress field and if so how would you propose making these changes or updates?

4. What roles do you see statistical quantification of NDI techniques playing in these potential changes?

5. What document do you see defining NDI capabilities within deep residual stress fields?

Questions to Answer (V1)

A Century of Scientific Excellence

- What is the current state-of-the-art of knowledge on the impact of deep residual stresses to various NDI methods?
- What requirements to you see the USAF putting out to better define the impacts of deep residual stresses on POD at coldworked (Cx) holes?
  - What additional testing/analysis must be performed to allow the fulfillment of these requirements?
- What type of document do you see being developed to provide users to know how deep residual stresses impact POD?
- What needs to happen from an NDI perspective for accounting for RS in USAF depot maintenance?
- How can the knowledge gained through the work on Cx holes be applied to other deep residual stress inducing processes like Laser Shock Peening or Low Plasticity Burnishing?

Agenda

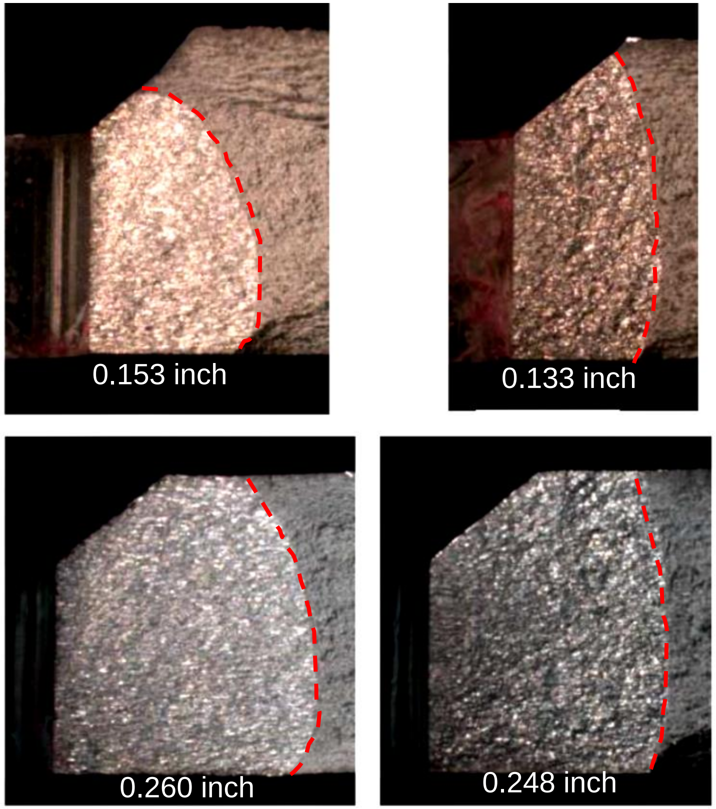
A Century of Scientific Excellence

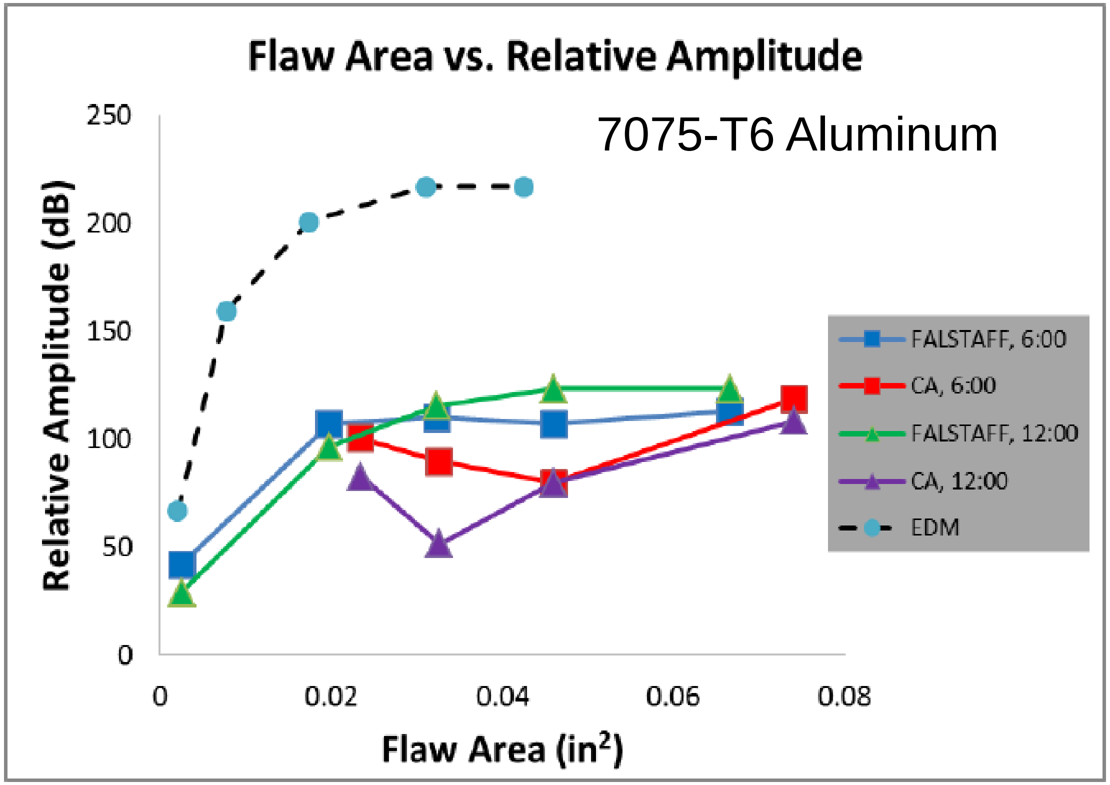
- Current Understanding
- Future Research Needs
- Guidance for Depot and Field Inspections
- Documenting Lessons Learned

EDM vs. Fatigue Cracks in Holes – No Load
Shear-Wave Ultrasonic Response

A Century of Scientific Excellence

FALSTAFF Constant Amplitude





Henry, T. "Correlating Ultrasonic Responses of Fatigue Cracks Propagated Under Different Load Spectra."

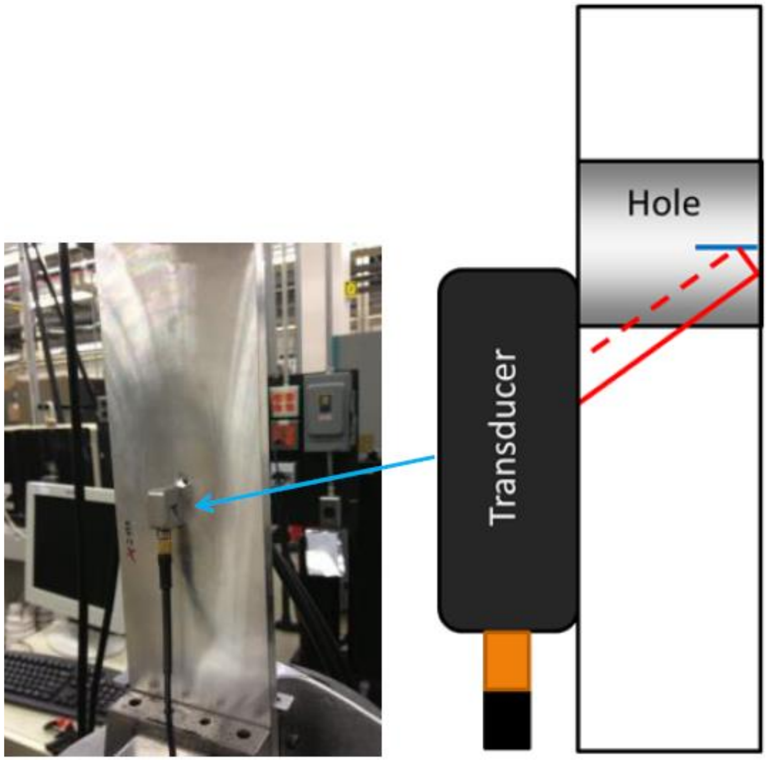
- UT response from EDM slots and fatigue cracks differ considerably.
  - 6dB difference between UT response from EDM and unloaded fatigue cracks
- UT response will vary depending on crack profile and fracture surface texture.

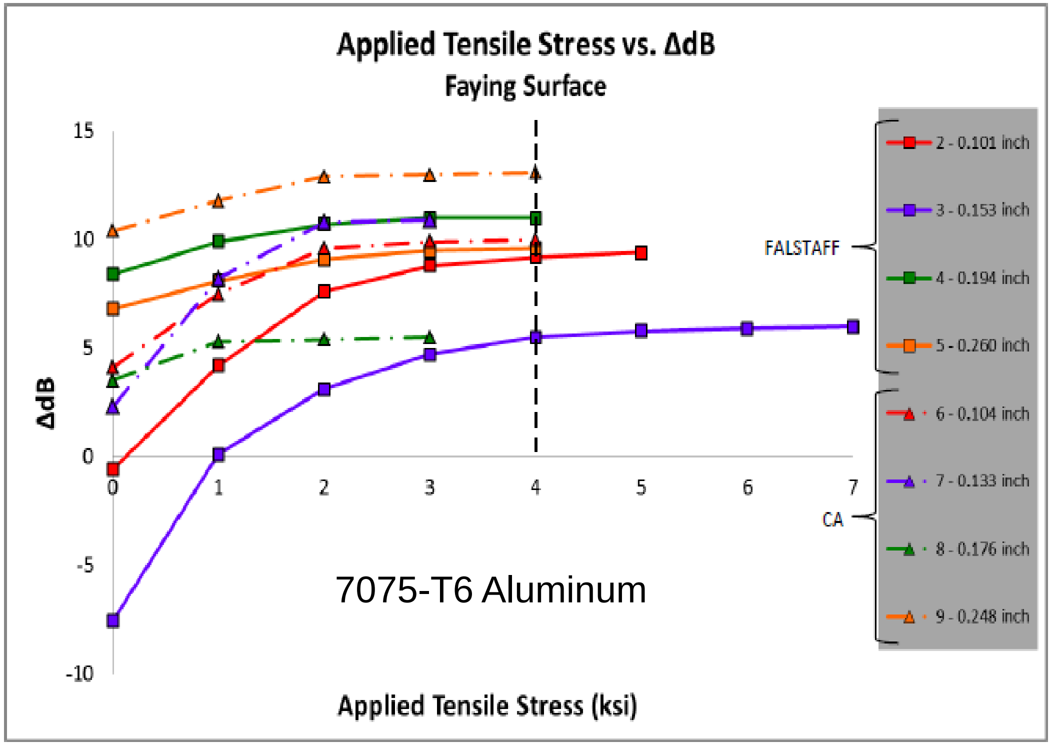
Return Energy a Function of Reflector Geometry Surface Texture, Crack Closure

Fatigue Cracks in Holes, Applied Tensile Stress
Shear-Wave Ultrasonic Response

A Century of Scientific Excellence

Tensile stress required to fully open fatigue cracks in holes w/o Cx.





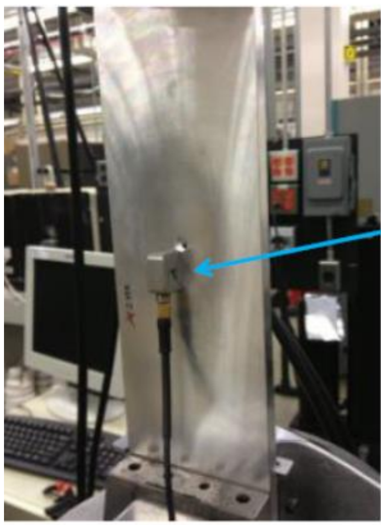
Henry, T. "Correlating Ultrasonic Responses of Fatigue Cracks Propagated Under Different Load Spectra."

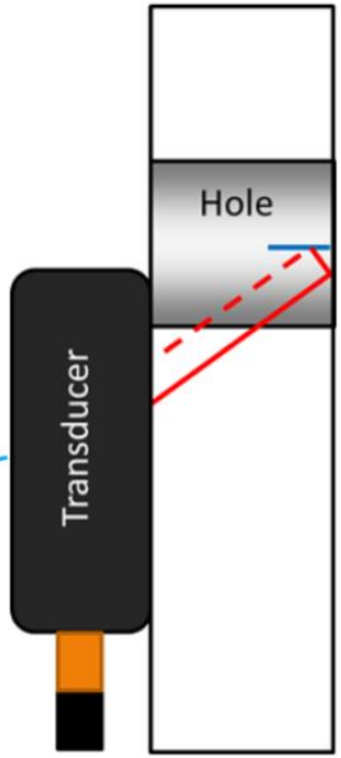
~ 4 ksi tensile stress sufficient to open crack for maximum UT detectability.

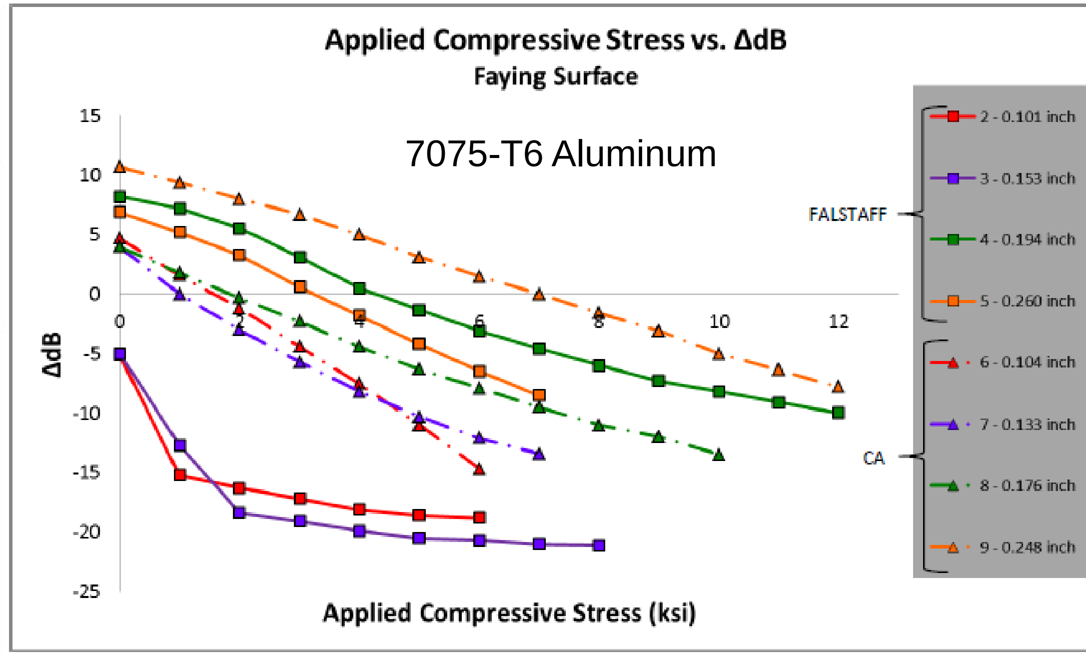
Fatigue Cracks in Holes, Applied Compressive Stress
Shear-Wave Ultrasonic Response

A Century of Scientific Excellence

Ultrasonic response from fatigue cracks under applied compressive stress.





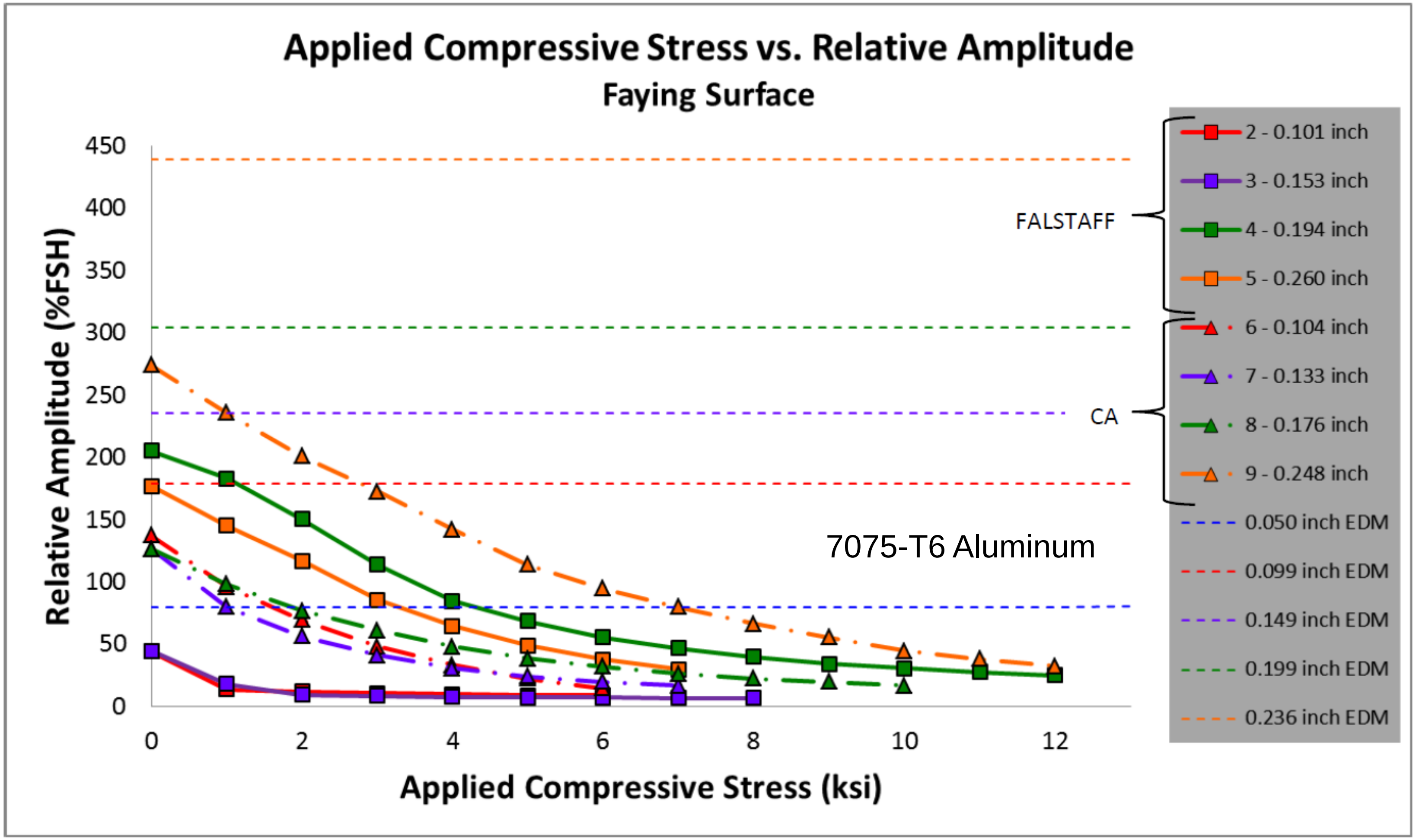


Henry, T. "Correlating Ultrasonic Responses of Fatigue Cracks Propagated Under Different Load Spectra."

~6dB (50%) signal reduction per 4 ksi applied compressive stress.

Fatigue Cracks in Holes, Applied Compressive Stress
Shear-Wave Ultrasonic Response

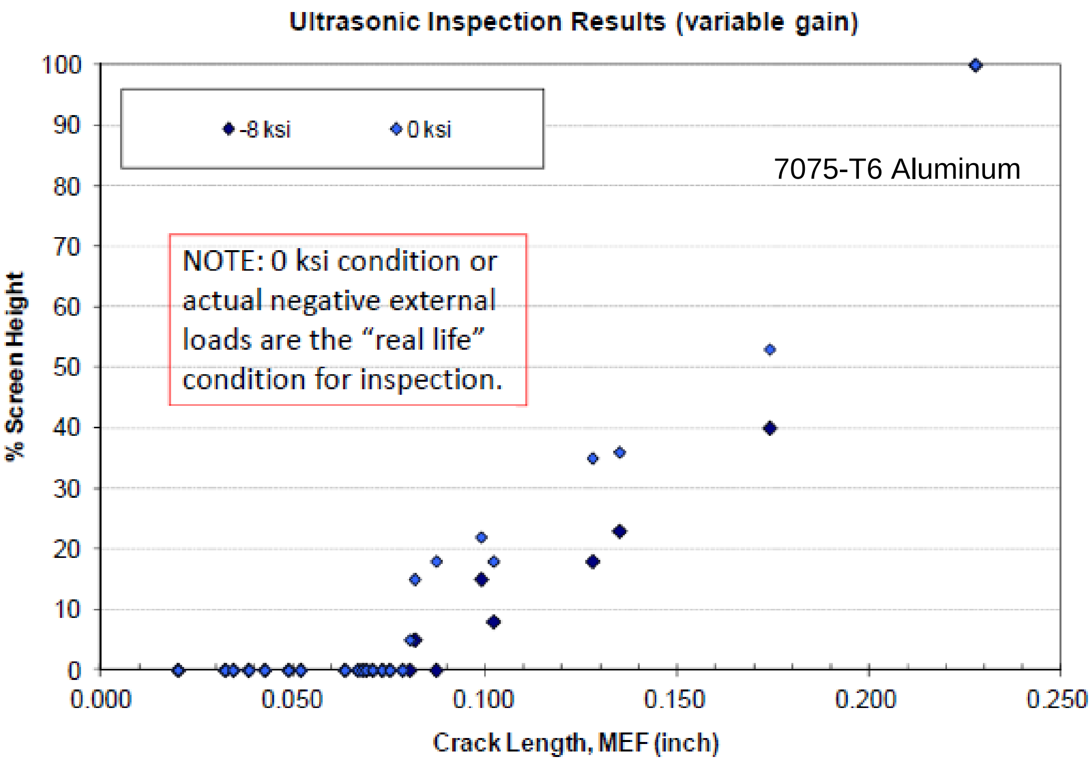
A Century of Scientific Excellence



Henry, T. "Correlating Ultrasonic Responses of Fatigue Cracks Propagated Under Different Load Spectra."

Fatigue Cracks Grown in Cx Holes, Applied Stress
Shear-Wave Ultrasonic Response

A Century of Scientific Excellence

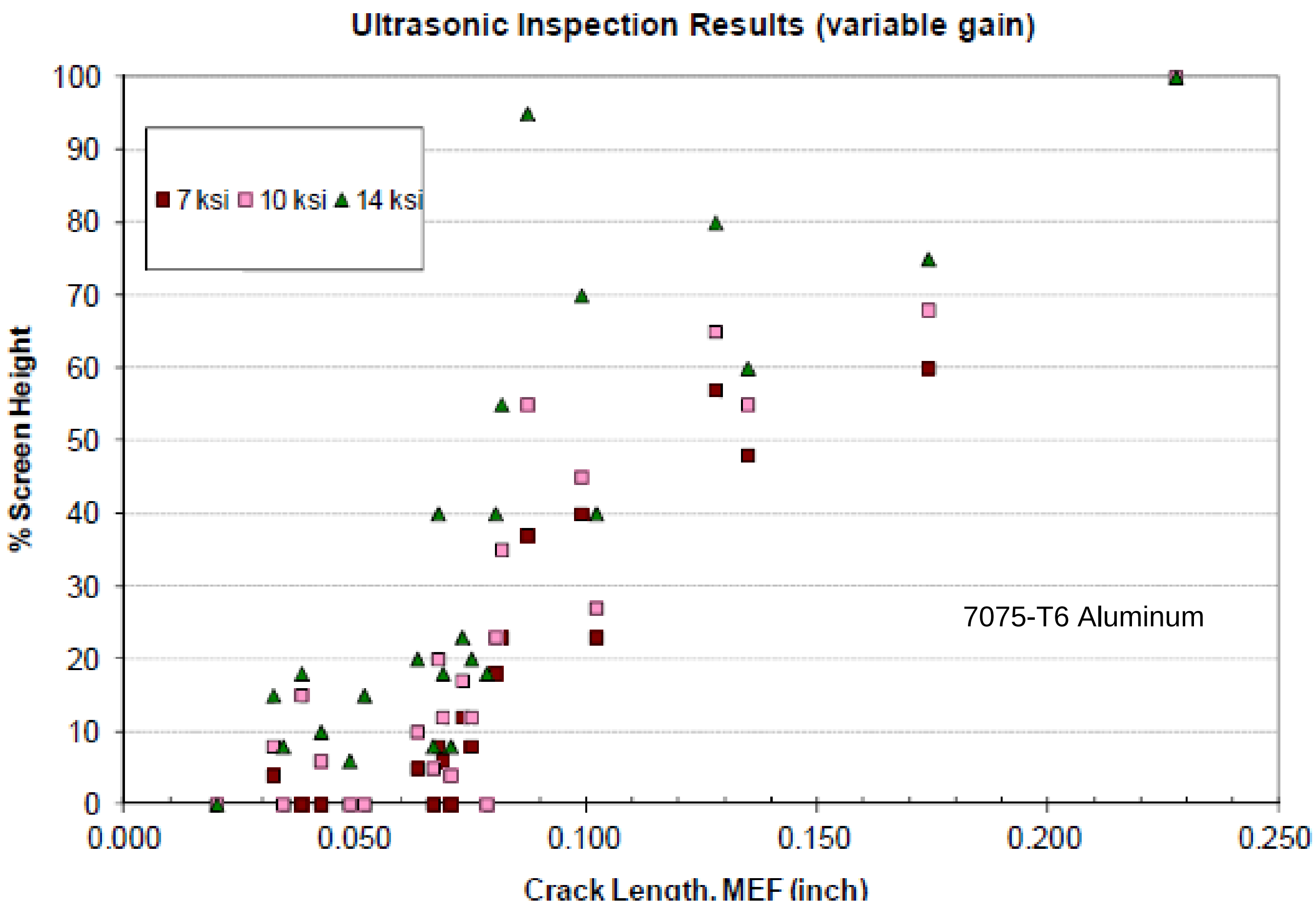


Forsythe, D., Mills, T. "Results of Study of Applied Stress and CX Process on Detectability of Fatigue Cracks"

- Crack must extend beyond compressive zone to be detectable by UT.
- Compressive stress zone extends >0.075 inch beyond edge of hole for this scenario.

Fatigue Cracks Grown in Cx Holes, Applied Stress
Shear-Wave Ultrasonic Response

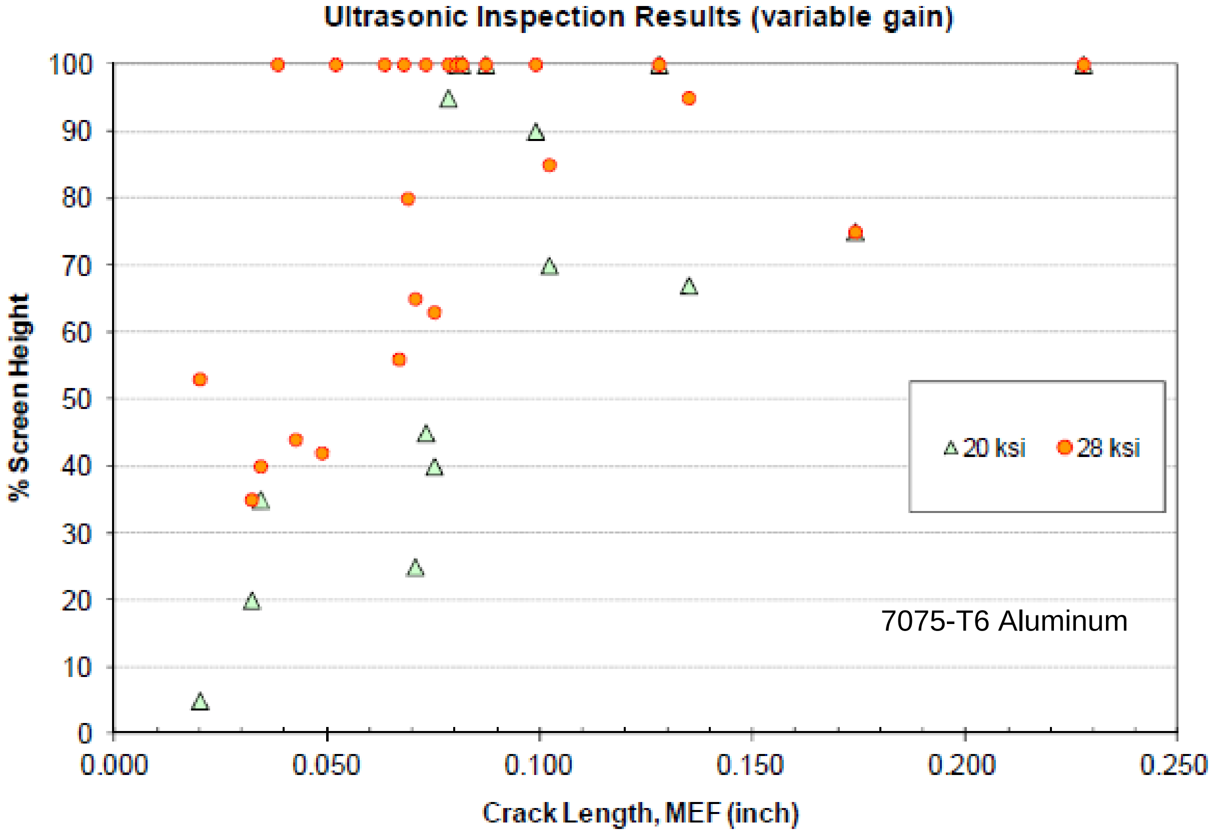
A Century of Scientific Excellence



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

Fatigue Cracks Grown in Cx Holes, Applied Stress
Shear-Wave Ultrasonic Response

A Century of Scientific Excellence



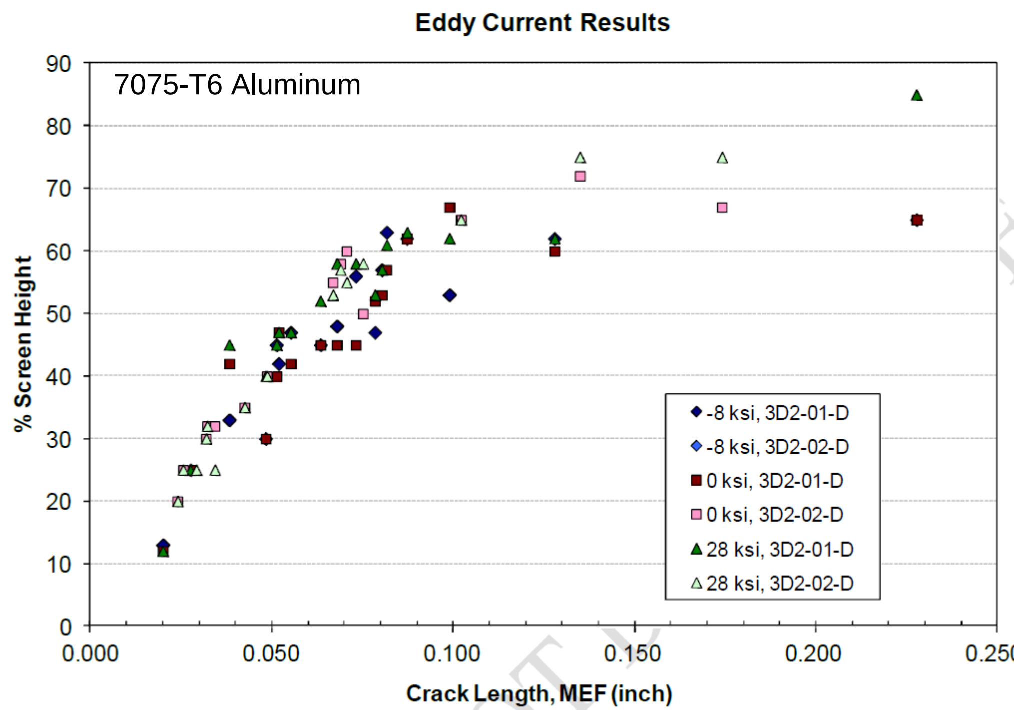
Forsythe, D., Mills, T. "Results of Study of Applied Stress and CX Process on Detectability of Fatigue Cracks"

Significant applied tensile stress required to fully open fatigue crack in CX holes

Fatigue Cracks Grown in Cx Holes, Applied Stress
Bolt Hole Eddy Current Response

A Century of Scientific Excellence

Rotary bolt hole eddy current response from fatigue cracks under compressive stress.



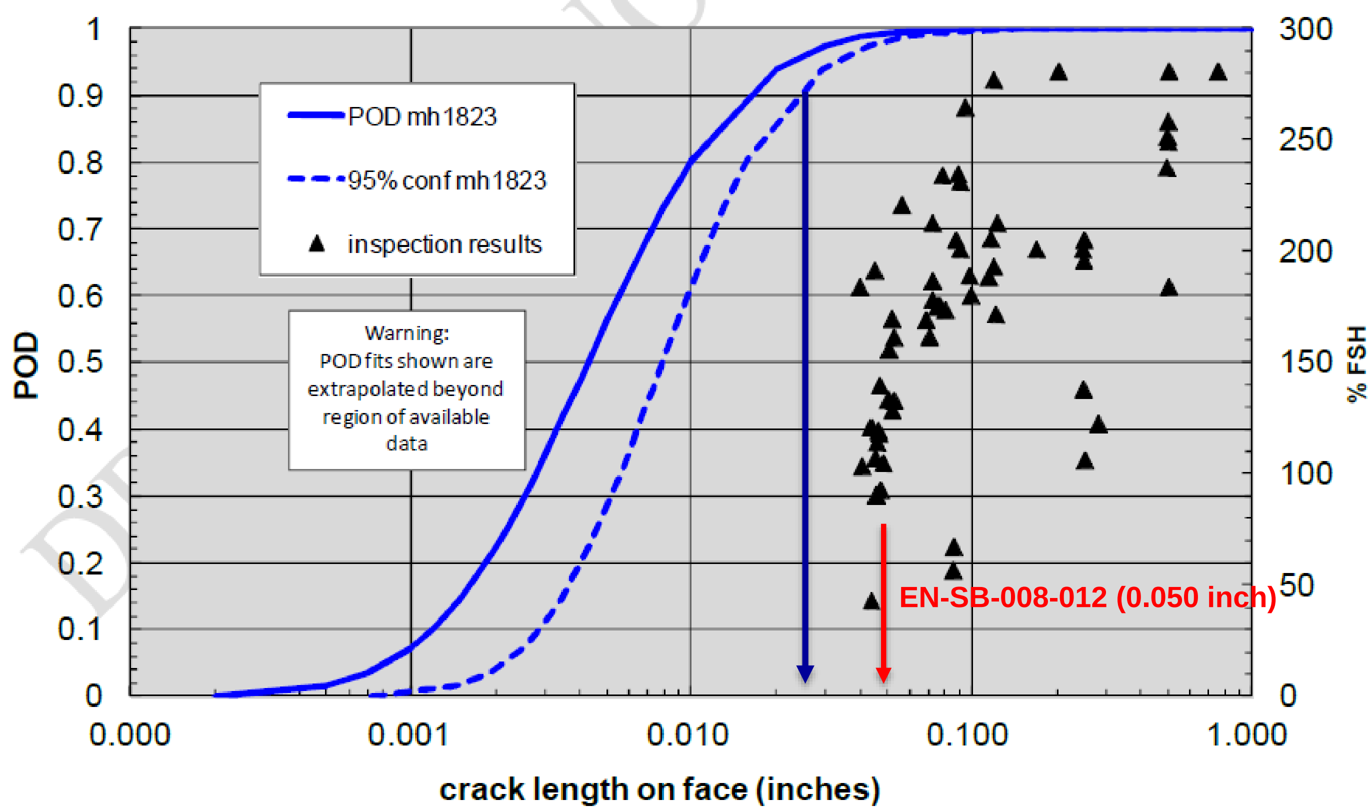
Forsythe, D., Mills, T. "Capability of Inspections for the Detection and Sizing of Cracks in Cold Worked Holes"

Applied compressive stress has no significant effect on rotary bolt-hole eddy current response.

Fatigue Cracks Grown in Cx Holes

Bolt Hole Eddy Current POD

A Century of Scientific Excellence



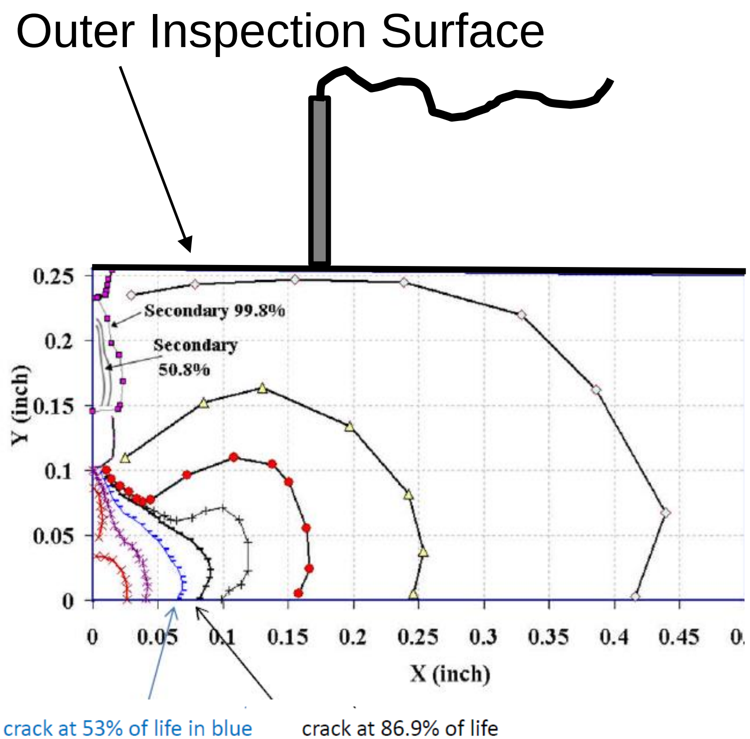
Forsythe, D., Mills, T. "Capability of Inspections for the Detection and Sizing of Cracks in Cold Worked Holes"

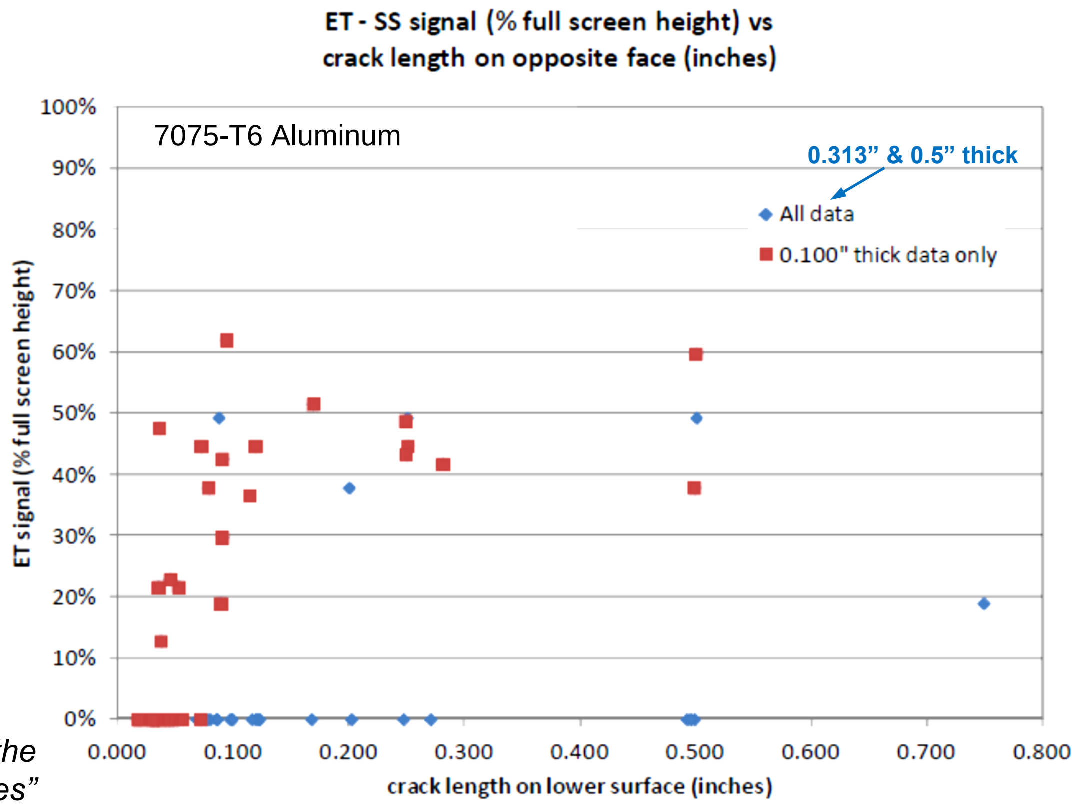
- Existing EN-SB-008-012 guidance is valid for BHEC in CX holes.

Fatigue Cracks Grown in Cx Holes

Surface Eddy Current Response

A Century of Scientific Excellence





Forsythe, D., Mills, T. "Capability of Inspections for the Detection and Sizing of Cracks in Cold Worked Holes"

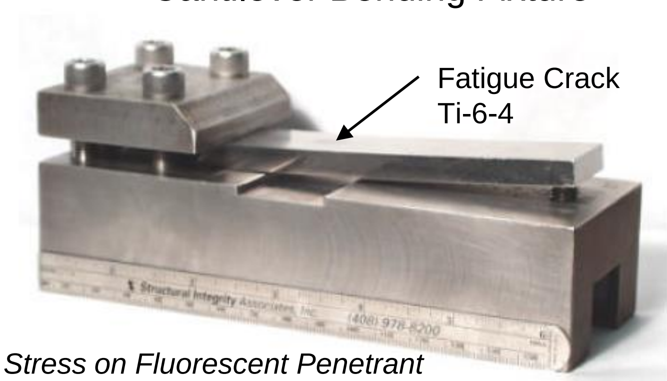
- Cracks in CX holes initiate at mandrel entry surface, typically faying surface.
- Cracks must grow to inspection surface to be detectable.
- Fatigue cracks in CX tend to "tunnel" under inspection surface.
- ***ECSS from mandrel exit surface not effective for plate thicknesses >0.100 inch!!***

Fatigue Cracks Under Applied Compressive Stress
Fluorescent Penetrant Response

A Century of Scientific Excellence

Result:
Significant measurable reduction in penetrant indication size with application of compressive stress.

Cantilever Bending Fixture



Measured residual surface stress (X-Ray Diff)

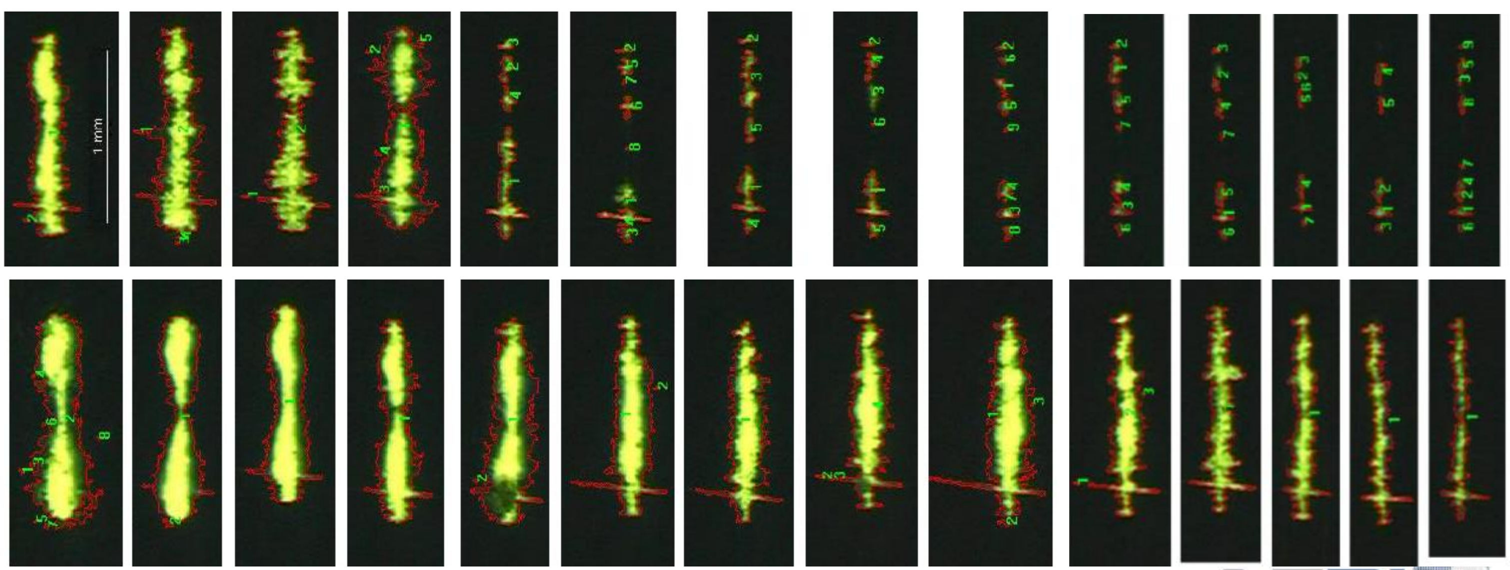
Specimen Number	Longitudinal Residual Stress (ksi) Before Annealing	After Annealing
17	-50.9 ± 4.5	4.2 ± 1.3 0.3 ± 2.1
63	-40.6 ± 2.3	-5.8 ± 1.8 -3.8 ± 1.2
41	-38.3 ± 4.5	0.9 ± 1.9 -0.1 ± 1.5
44	-35.7 ± 3.3	-4.1 ± 1.5 1.7 ± 1.5
53	-60.3 ± 3.6	-2.8 ± 1.6 -3.1 ± 1.4

Brausch, J., Tracy, N., Effects of Compressive Stress on Fluorescent Penetrant Indications of Fatigue Cracks in Titanium, AFRL-ML-WP-TR-2001-4139

Applied Stress (ksi) 0 3.5 8.5 13.5 18.5 23.5 28.5 33.5 38.5 43.5 48.5 53.5 58.5 63.5

Specimen #44

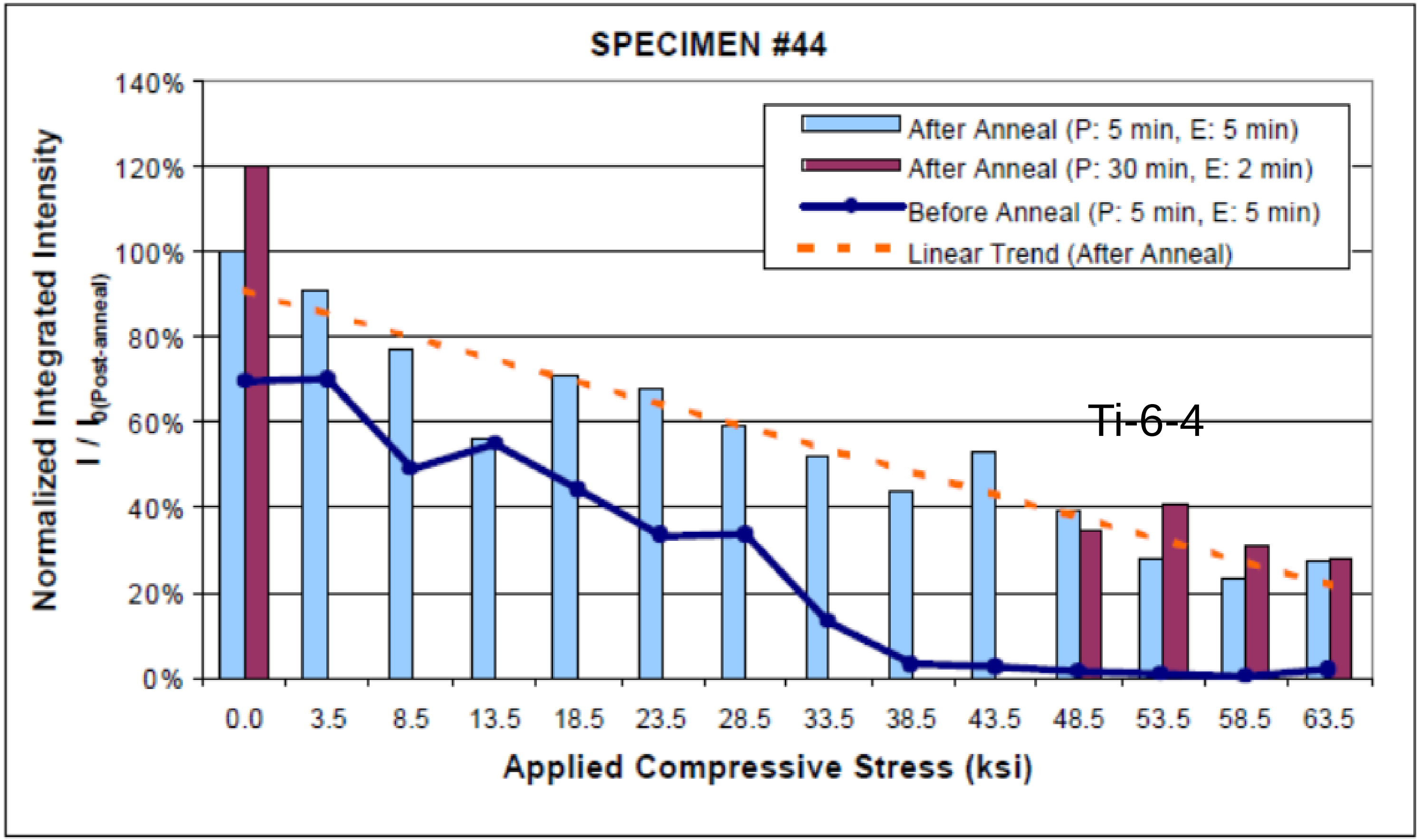
Post Stress Relief



Fatigue Cracks Under Applied Compressive Stress
Fluorescent Penetrant Response

A Century of Scientific Excellence

- Combined effect of residual and applied stress is significant.
- Increased penetrant dwell times generally improved performance.

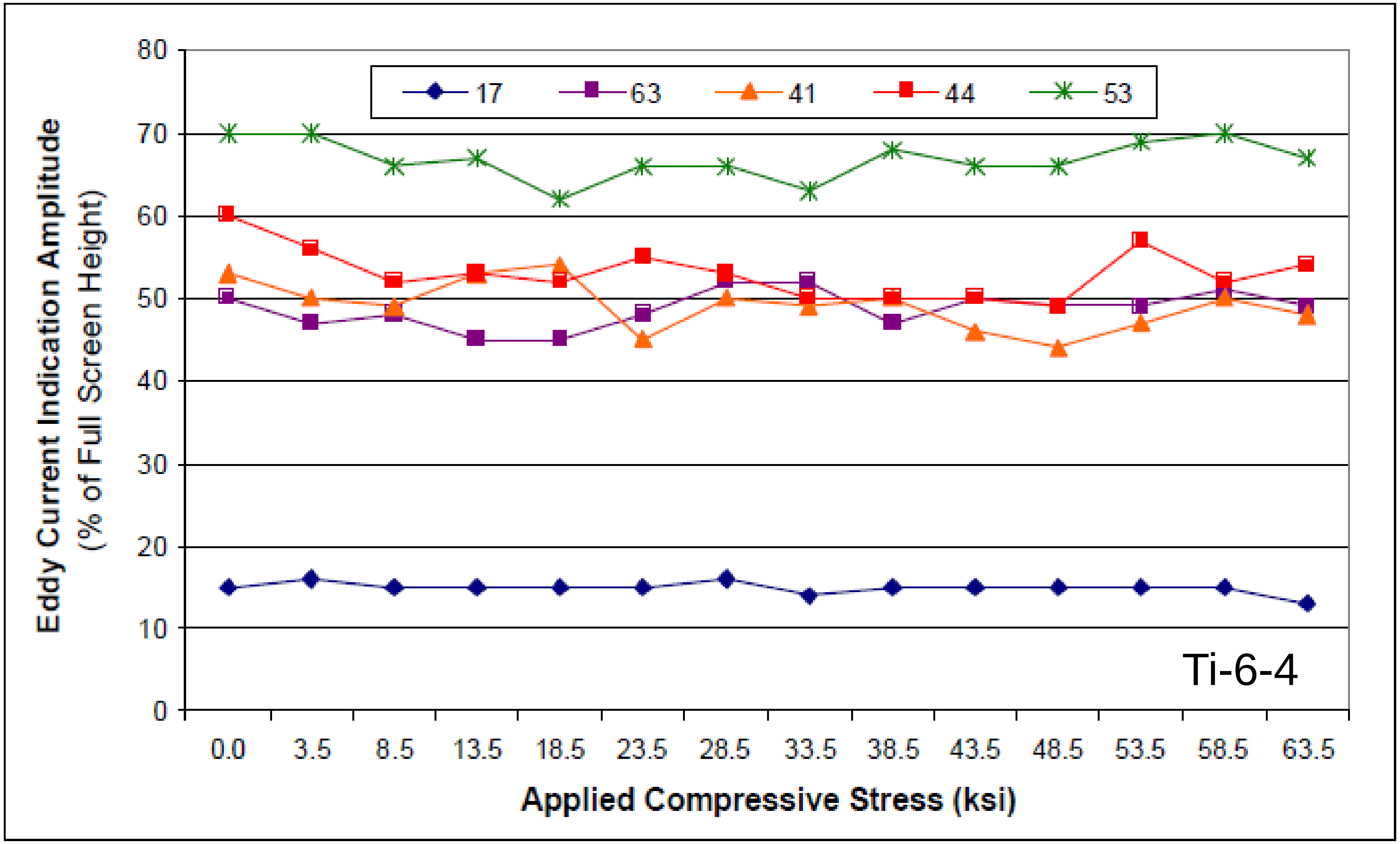


Brausch, J., Tracy, N., Effects of Compressive Stress on Fluorescent Penetrant Indications of Fatigue Cracks in Titanium, AFRL-ML-WP-TR-2001-4139

Fatigue Cracks Under Applied Compressive Stress
Eddy Current Response

A Century of Scientific Excellence

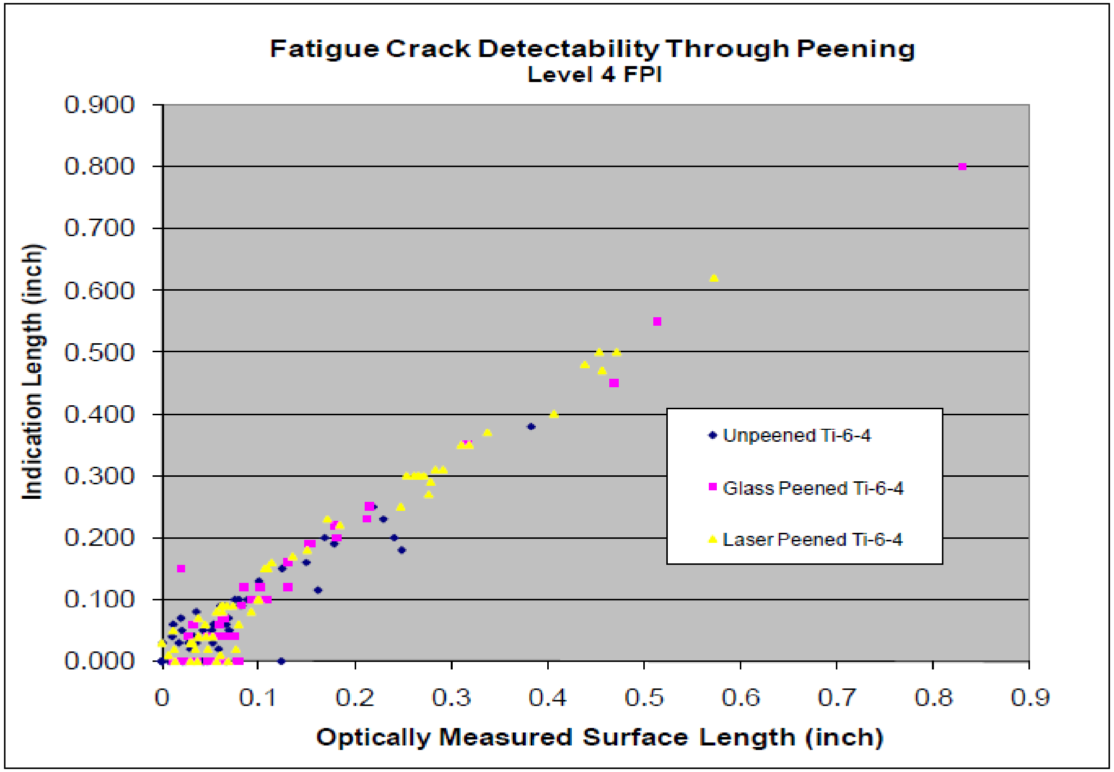
- No significant change in eddy current response up to 63.5 ksi.

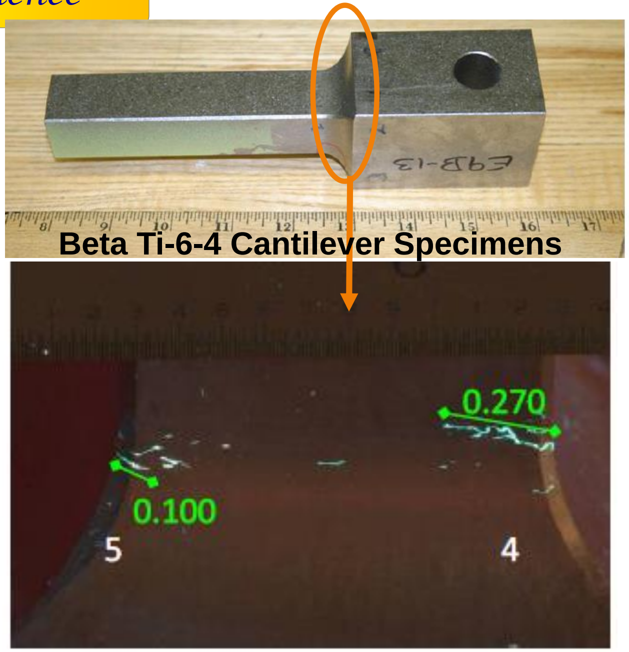


Brausch, J., Tracy, N., Effects of Compressive Stress on Fluorescent Penetrant Indications of Fatigue Cracks in Titanium, AFRL-ML-WP-TR-2001-4139

Fatigue Cracks Grown Through Deep Residual Stress
Fluorescent Penetrant Response

A Century of Scientific Excellence





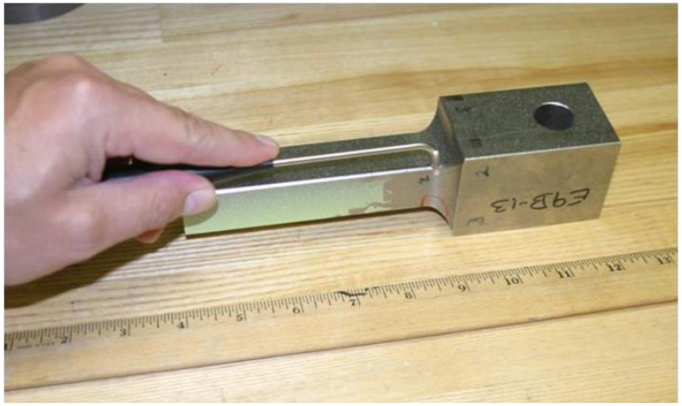
Penetrant:	Sherwin RC-77
Solvent Remover:	Isopropyl Alcohol
Developer:	Magnaflux ZP-4B
Penetrant Dwell Time:	60 minutes
Developer Dwell Time:	15 minutes

- FPI indication lengths compared well to optically measured fatigue crack surface lengths for:
  - Unpeened Ti-6-4
  - Glass Peened Ti-6-4 (MIL-STD-13165, BAC 5730)
  - Laser Peened Ti-6-4 (AMS 2546)
- Indications were clearly discernible **but exhibited less bleed-out on peened surface**.

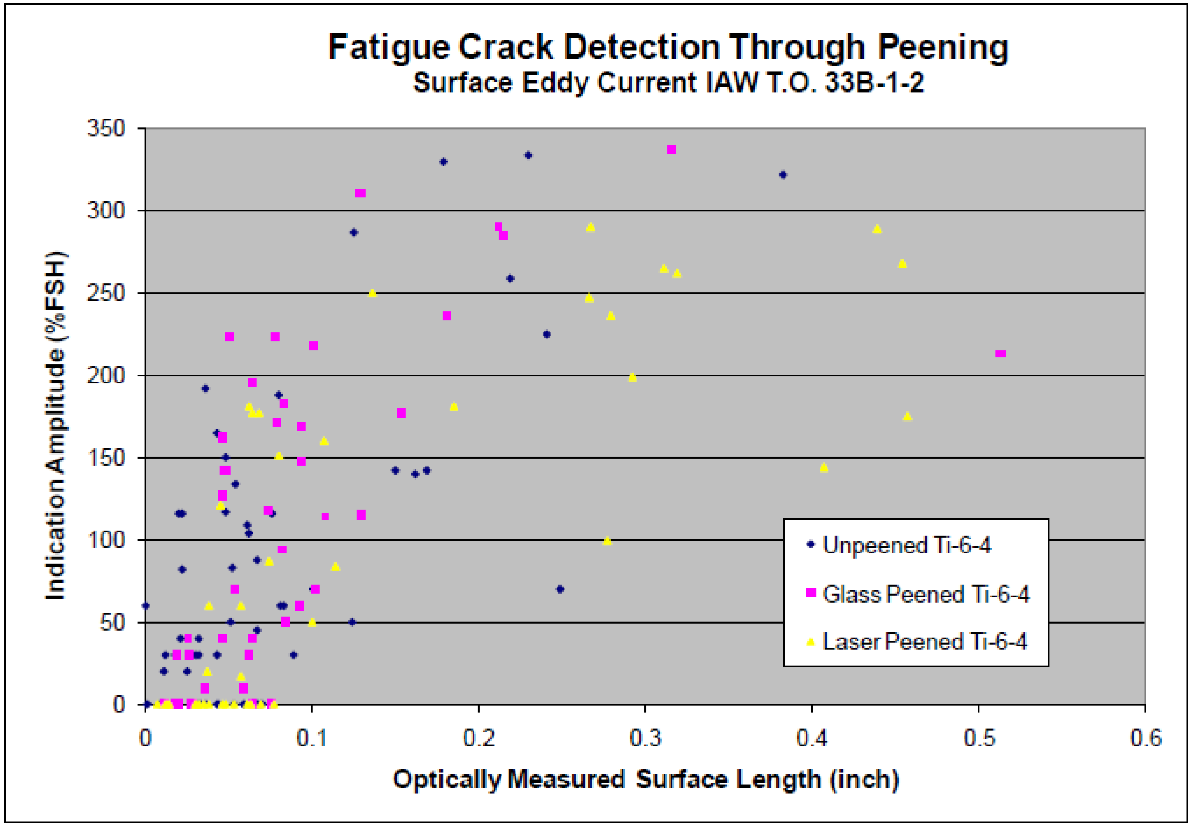
Fatigue Cracks Grown Through Deep Residual Stress
Surface Eddy Current Response

A Century of Scientific Excellence

Beta Ti-6-4 Cantilever Specimens



Eddy Current Inspection
IAW T.O. 33B-1-2, WP 402

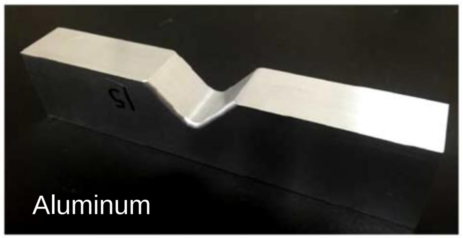


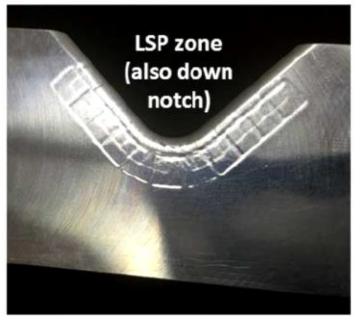
- Surface eddy current response exhibits typical scatter induced by human variance.
- Fatigue cracks within unpeened, glass-peened and laser-peened Beta Ti-6-4 exhibited comparable SECI detectability.

Laser Peening Study
Preliminary Surface Eddy Current Results

A Century of Scientific Excellence

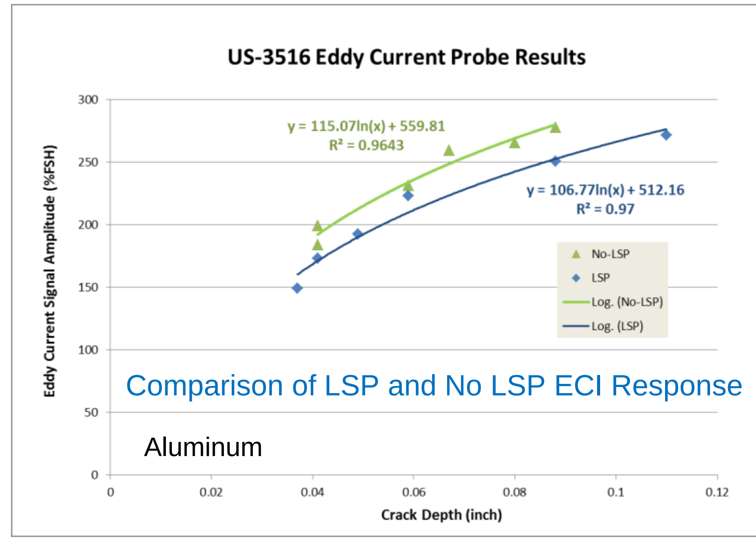
Typical bend bar blank with chamfered notch

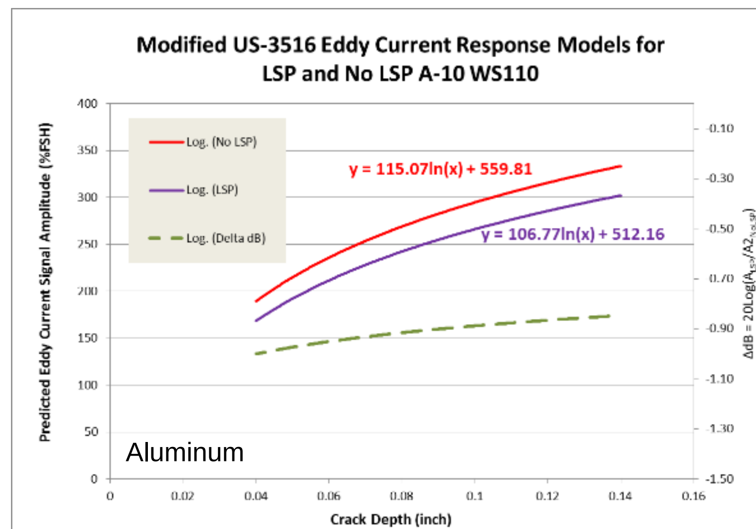




Courtesy of Hill Engineering, LLC

J. *Brausch, W. Fong, Briefing Charts to Hill Engineering, March 2016.*





- Separation between ECI response from LSP and No-LSP results suggests two populations yielding two ECI response models
- Less than 1 dB deviance between the LSP and No LSP models.
- **<1dB shift is well within typical calibration tolerance and typical POD assumptions.**
- Possible sources of shift: crack morphology, crack closure, crack profile, local conductivity change resulting from cold work.
- Phase II work underway: includes ECI and FPI characterization of cracks grown in peened and unpeened surfaces.

AFRL

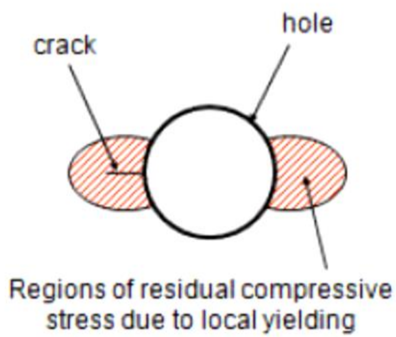
Other Works

A Century of Scientific Excellence

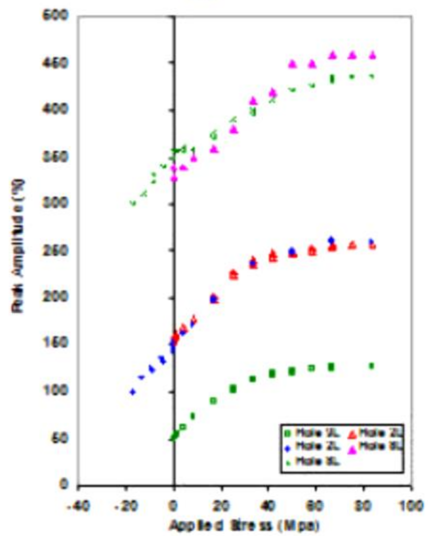
Preliminary Results

Australian Government
Department of Defence
Defence Science and Technology Organisation

Crack closure due to plastic strain at holes (notch plasticity)



Effect of applied load on UT



Harding, C. A., Hugo, G. R., & Bowles, S. J. (2006, March). Model-Assisted POD for Ultrasonic Detection of Cracks at Fastener Holes. Presented at RPQNDE 2005. In *AIP Conference Proceedings* (Vol. 820, p. 1862).

Harding, C. A, Hugo, G.R., & Bowles, S.J. (2006 March), "Model-Assisted POD for Ultrasonic Detection of Cracks at Fastener Holes", Presented at RPQNDE 2005. In AIP Conference Proceedings (Vol 820, p1862)

L.J. Nelson, K. Brown, A Young, L.D. Jones and R.A. Smith "Ultrasonic Detectability of Potentially Closed Cracks from Cold-Worked Holes Under Loaded Conditions", Presented at NDT 2007, 46th Annual British Conference on NDT, 2007.

Summary of Current Knowledge

A Century of Scientific Excellence

- Ultrasonic response from EDM and unloaded fatigue cracks differ by ~ 6dB for aluminum.
- Applied compressive stress reduces ultrasonic signal amplitude 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

A Century of Scientific Excellence

- CX of holes **reduces** ultrasonic detectability of fatigue cracks
  - A function of hole diameter, plate thickness
  - Detectability begins beyond the compressive field.
- Deep residual stress surface treatments **do not** significantly affect SECI detectability in aluminum or titanium.
- Deep residual stress surface treatments **may affect** fluorescent penetrant detection capability - further study required.

Future Research Needs

A Century of Scientific Excellence

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 (using POD inputs) to address component geometry, plate thickness, hole diameter, % hole expansion, hole fill
- Conduct empirical sensitivity studies to calibrate model.

II. Study effects of deep residual stress on crack closure and fluorescent penetrant inspection on 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.

Guidance for Depot and Field Inspection

Holes without CX (Aluminum):

- Perform BHEC whenever possible.
- SECI effective for surface breaking cracks
- For ultrasonics, apply 4ksi tensile stress by jacking or other means to open cracks for optimum UT detectability.
- Add >6dB gain above calibration to account for:
  - Crack closure of unloaded cracks.
  - Difference between fatigue crack and EDM notch UT response.
  - Coupling variance.
- If applied compressive stress (i.e. ground loads) can be estimated and jacking is not practical:
  - Add 6dB gain per 4ksi of compressive stress.

Holes with CX:

- Perform BHEC whenever possible
- SECI may be ineffective for small crack detection from mandrel exit surface
- Consider ultrasonic inspection if fasteners cannot be removed. Further study needed to quantify ultrasonic detection capability.
  - Assume detection capability begins beyond CX zone.
- Low frequency eddy current inspection may be considered as an alternative if large crack sizes can be tolerated.

Guidance for Depot and Field Inspection

Surfaces with Deep Residual Stress Treatments:

- Perform both surface eddy current and fluorescent penetrant inspections
- Extend fluorescent penetrant dwell times to 60 minutes minimum.
- Ensure surface treatments do not result in crack tunneling.

Documenting Lessons Learned

A Century of Scientific Excellence

- Incorporate current and updated knowledge into T.O. 33B-1-1.
- Develop and incorporate shear-wave ultrasonic inspection procedures in T.O. 33B-1-2 for manual inspection around fastener holes.
- Modify existing NDI field and depot procedures to implement best NDI practices for CX and deep residual stress treatments.
  - ***Engineering must identify structures where CX or peening has been applied. Not typically identified.***
- Incorporate POD guidance into EN-SB-08-012
  - Surface eddy current limitations from mandrel exit surface for CX holes.
  - Shear-wave ultrasonic detection capability guidelines.
  - Establish validated models for POD estimation based on plate thickness, hole diameter, % hole expansion. Reference models is the SB.

References

A Century of Scientific Excellence

Henry, T. “Correlating Ultrasonic Responses of Fatigue Cracks Propagated Under Different Load Spectra.” Honors Thesis, Department of Chemical and Materials Engineering, University of Dayton, April 2013

Forsythe, D., Mills, T., “Capability of Inspections for the Detection and Sizing of Cracks in Cold Worked Holes”, Report: Task 9, Contract # FA9453-12-C-0218.

Brausch, J., Tracy, N., “Effects of Compressive Stress on Fluorescent Penetrant Indications of Fatigue Cracks in Titanium”, AFRL-ML-WP-TR-2001-4139, March 2001.

Harding, C. A, Hugo, G.R., & Bowles, S.J. “Model-Assisted POD for Ultrasonic Detection of Cracks at Fastener Holes”, Presented at RPQNDE 2005. In AIP Conference Proceedings (Vol 820, p1862), March 2006.

L.J. Nelson, L.J., Brown, K, Young, A., Jones, L.D., Smith, R.A., “Ultrasonic Detectability of Potentially Closed Cracks from Cold-Worked Holes Under Loaded Conditions”, Presented at NDT 2007, 46th Annual British Conference on NDT, 2007.

Questions

A Century of Scientific Excellence