Studies on EC Inspection and Modeling toward MAPOD Applications

B. F. Larson and N. Nakagawa

This material is in part based on work supported by the Air Force Research Laboratory under contract #FA8650-040C-5228 at Iowa State University's Center for NDE.

Objectives of the Project

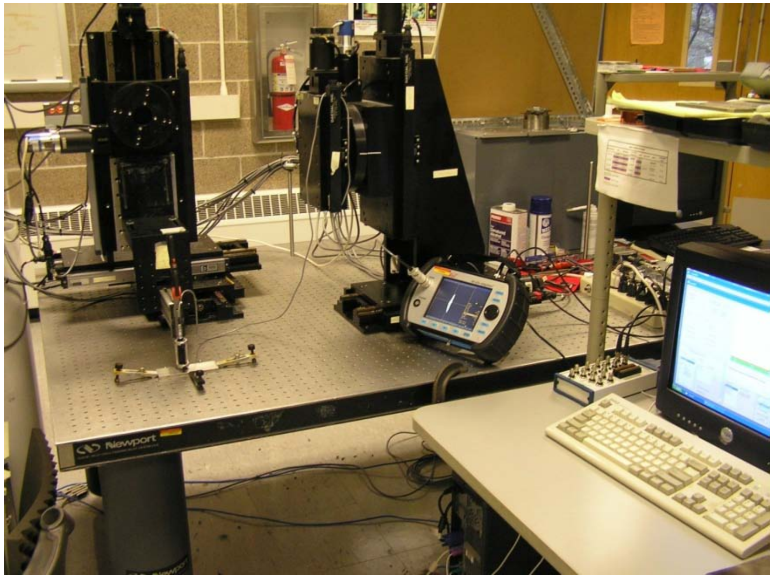
- To validate the EC models
  - Establish the relationship between model predictions and experimental observations, while assessing accuracy and capability limits leading to necessary developments and/or improvements.
- To develop the next-generation EC model code
  - Implementing the needed capabilities (crack response, notch response, and geometry response in a single software tool) for use in model-assisted POD methodologies.
- To search for practical methods for characterizing probes

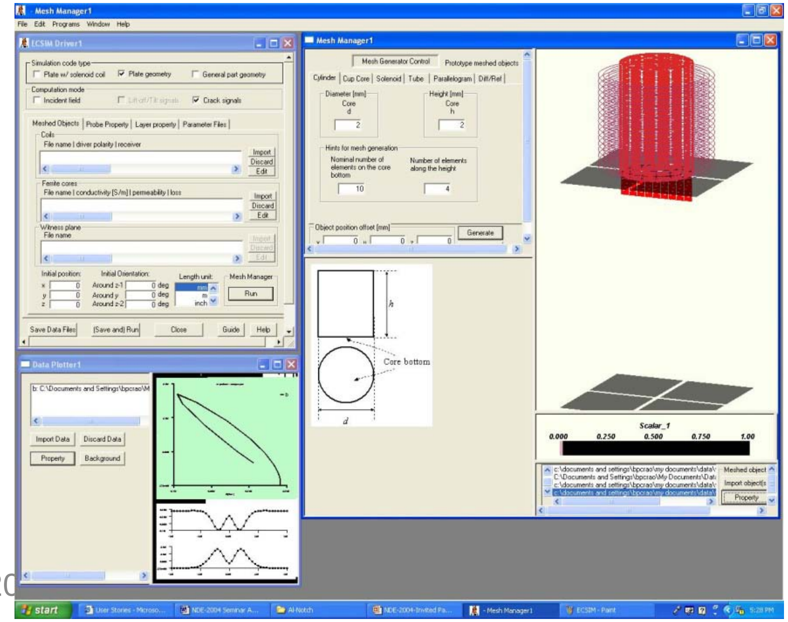
The long-term objectives:

- To develop a model-assisted EC POD methodology.
- To develop a fully validated EC model code
  - Applicable to the model-assisted POD (MAPOD) methodology.

Approach

- EC model validation
  - Develop and exercise validation protocol
  - Acquire validation data with notch and crack specimens.
- Model development
  - Generate theory data according to the protocol
- MAPOD demonstration
  - Develop criteria of success for MAPOD application
  - MAPOD case study





NOTCHES VS. CRACKS: EFFECTS ON EDDY CURRENT NDE SIGNALS FROM DEFECT VOLUMES AND FROM CRACK MORPHOLOGY ALTERED BY MECHANICAL LOADING

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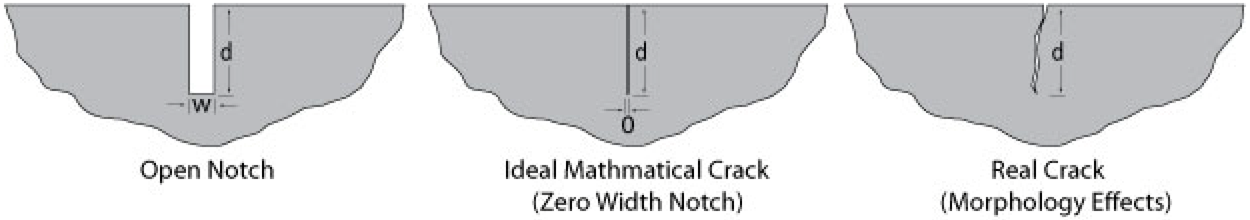
Outline

- Introduction
- Review of Previous Work
- Specimens
- Probes and Experimental Setup
- Results
- Future Plans
- Summary

Introduction

- The objective of this study is to investigate the effect that discontinuity width and crack loading has on the eddy current signal.

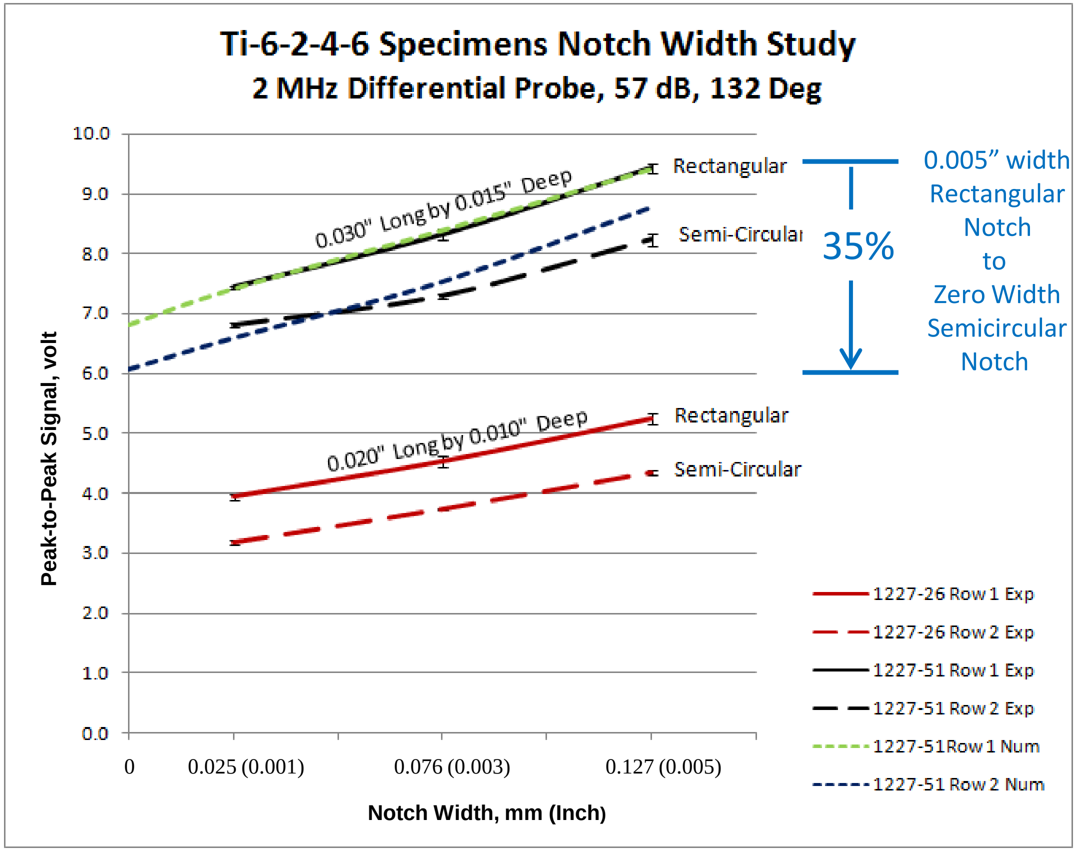
- This study is part of broader ongoing study with the objective to investigate the influence that defect morphology has on NDE signals.



Previous Work on Notch Width Effect

In previous work the authors have shown that the notch width effect is relatively linear over the crack length range of interest and can be numerically modeled to produce an estimate of the zero width notch.

How does the zero-width notch signal compare to a fatigue crack signal?



Ref: N. Nakagawa, M. Yang, B. Larson, E. Madison, and D. Raulerson, Study of the Effects of EDM Notch Width on Eddy Current Signal Response, Review of Progress in QNDE, Volume 28, pp. 287-294 (2008)

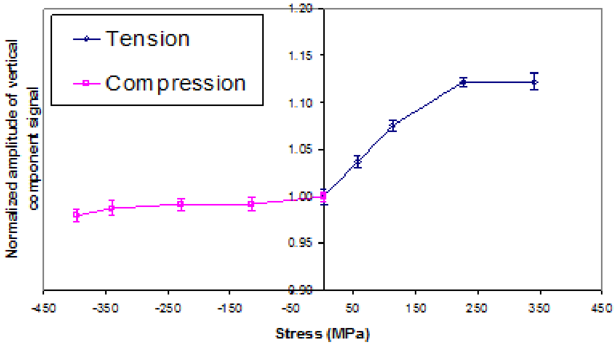
Previous Work on Crack Loading

Previous work has also been shown that:

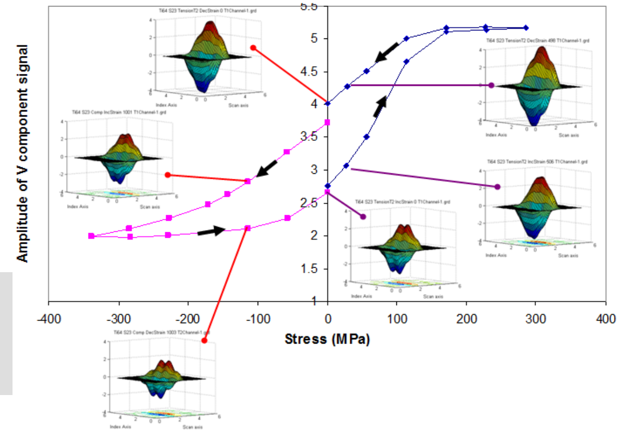
- For fatigue crack samples in Al 6061:
  - Under tension, the EC signals increase and signal changes are larger for longer cracks.
  - Under compression, crack signal remains relatively unchanged. (Possibly due to an insulating oxide layer on the crack faces.)
- For fatigue cracks in Ti 6-4:
  - Substantially larger signal changes than those in the Al samples were seen under both tension and compression.
  - A hysteresis effect was noted over the stress cycle.

How do these signals compare to a zero-width notch signal and is this hysteresis effect unique to Ti?

Al: crack length = 4.95mm (0.195")



Ti: crack length = 2.90mm (0.114")



Ref: C.C.H. Lo and N. Nakagawa, Effects of Dynamic and Static Loading on Eddy Current NDE of Fatigue Cracks, Review of Progress in QNDE, Volume 28, pp. 355-362 (2008)

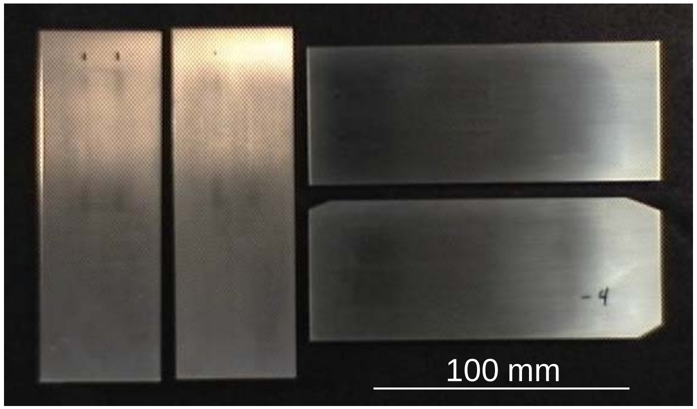
Materials and Specimens

- Notches and Cracks
  - EDM Notches
    - Ti6-2-4-2 and Ti6-4 STA
      0.580 & 0.597 MS/m (1.03 & 1.00% IACS)
    - IN100 and Inconel 718
      0.748 & 0.870 MS/m (1.29 & 1.50% IASC)
    - Al 6061-T6
      27.74 MS/m (47.8% IACS)

    2:1 and 3:1 Length to Depth Aspect Ratios
  - Cracks
    - Al 6061, Inconel 718 and Ti6-4

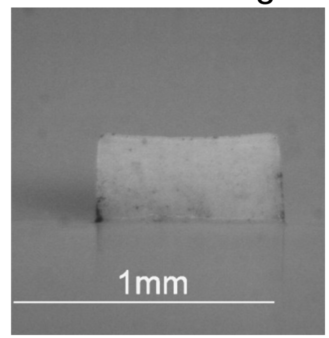
    2.8:1 Length to Depth Aspect Ratio

Notch Width Specimens

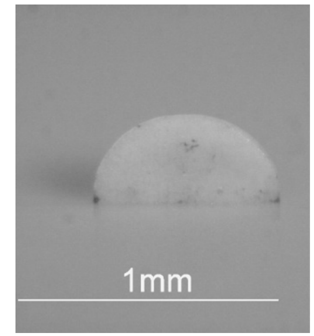


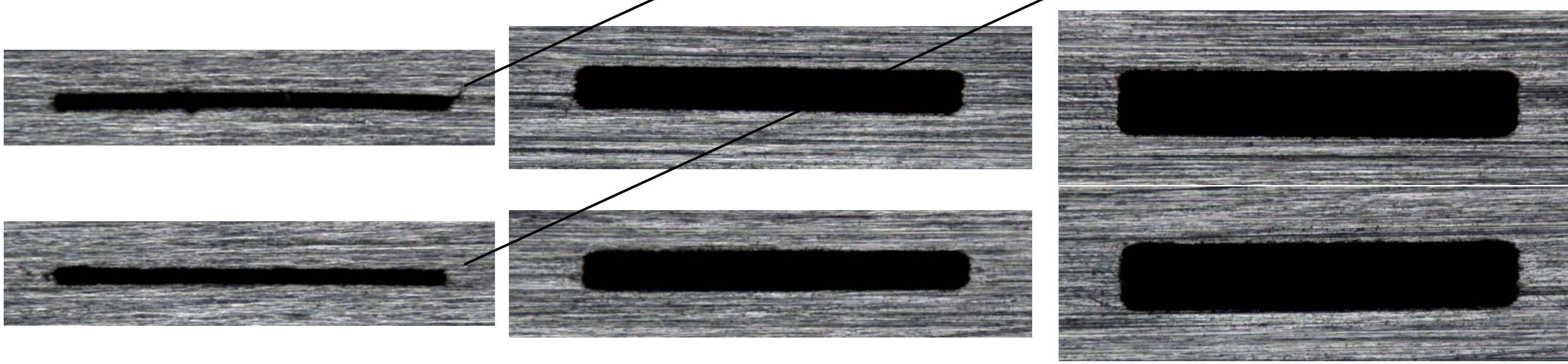
Overall Photo of Typical Notch Specimens

Row 1 - Rectangular



Row 2 – Thumbnail



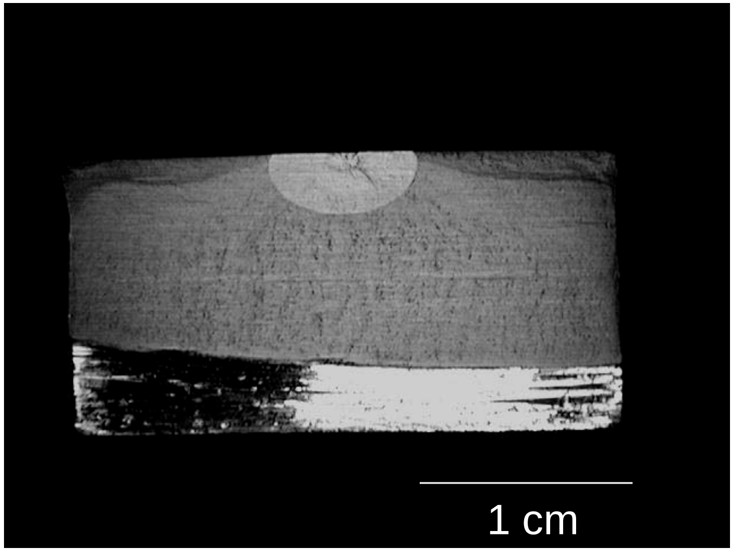


0.0254mm (0.001”) Wide | 0.0762mm (0.003”) Wide | 0.127mm (0.005”) Wide

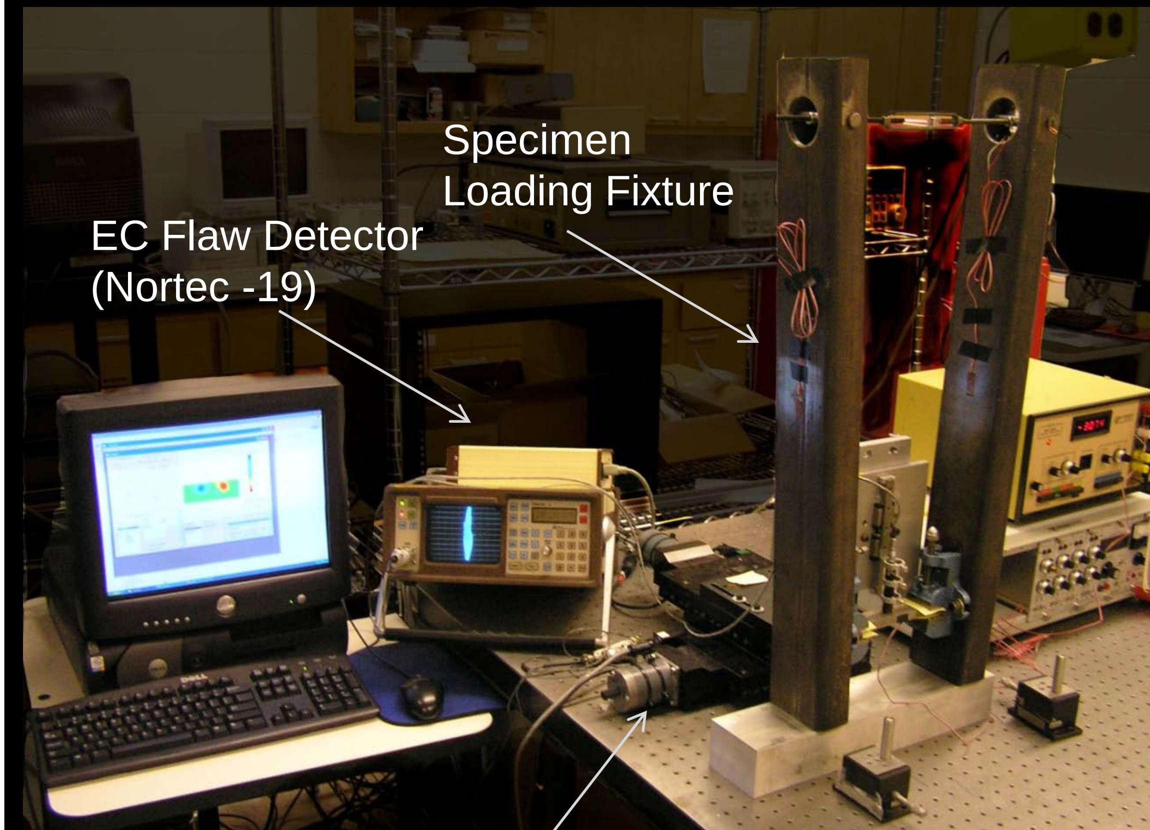
Close-up Photo of Notches in Specimen 1227-51 (0.030” Long by 0.015” Deep)

LCF Crack Specimens

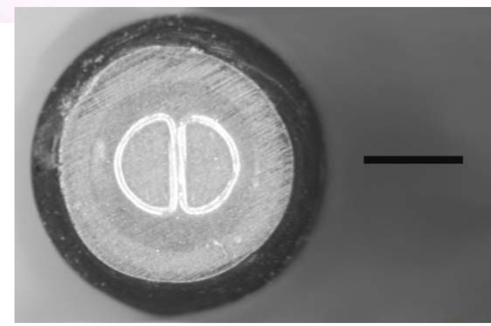
- Low cycle fatigue cracks specimens were produced for a fluorescent penetrant inspection study.
- The specimens were produced in three point bending with a max load of 80% of yield strength and an R ratio of 0.1.
- The surface was milled and ground to remove the starter notch.
- The crack length to depth aspect ratio was 2.8.
- All the specimens were 15cm (6”) long, 1.27cm (0.5”) thick and either 2.54cm (1”) (Al and Ti) or 3.8cm (1.5”) (Inconel) wide.



Experimental Setup



Motion Control and Data Acquisition | Scanning System | Specimen | Strain Gage Equipment

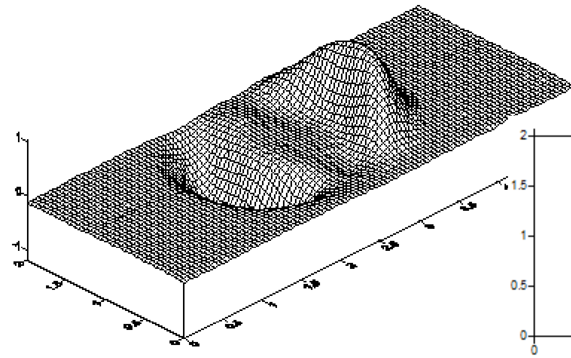


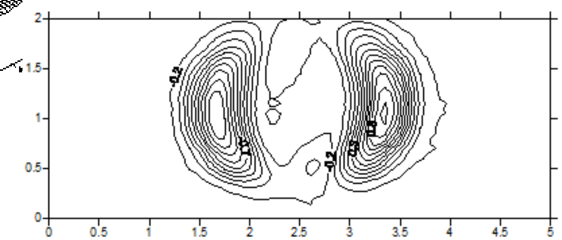
Coil Diameter: 1.83mm (0.072")

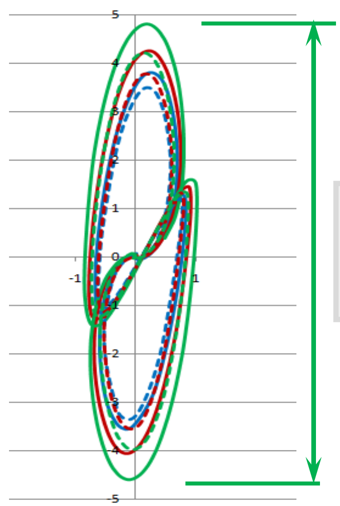
2 MHz Differential Probe was used with the coil gap aligned perpendicular to the notch/crack length.

Data Collection and Processing

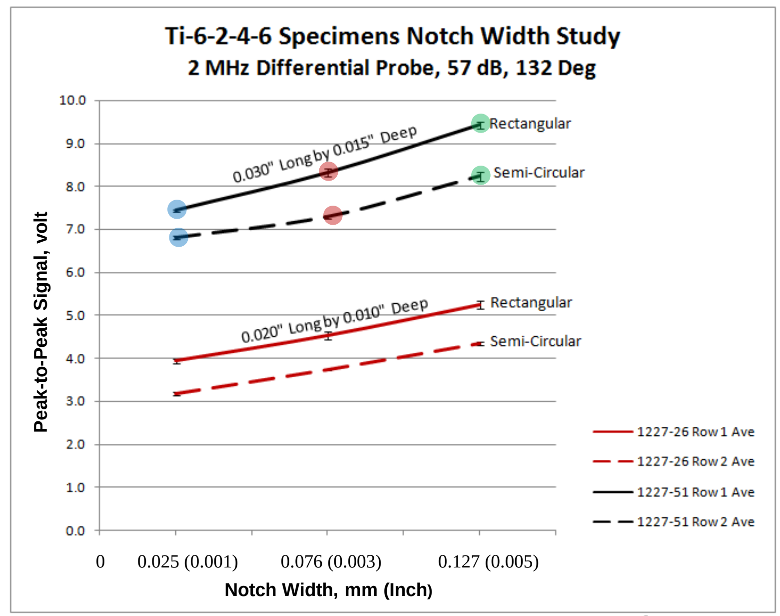
- Raster scans were collected (scan spacing = 0.05mm).
- The peak-to-peak signal voltage was recorded for each notch/crack from the processed data.



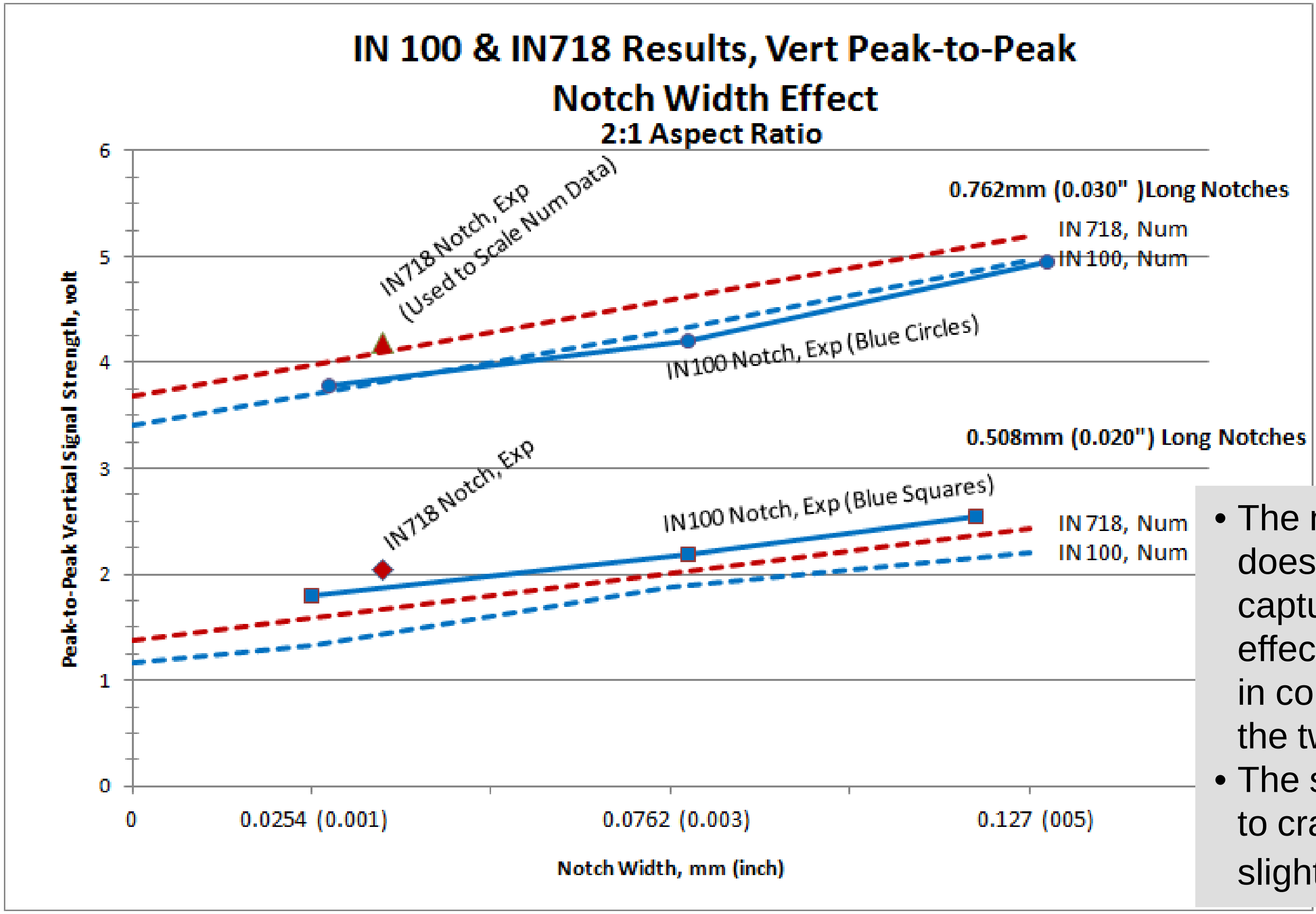




Peak-to-Peak
Max Values
Plotted

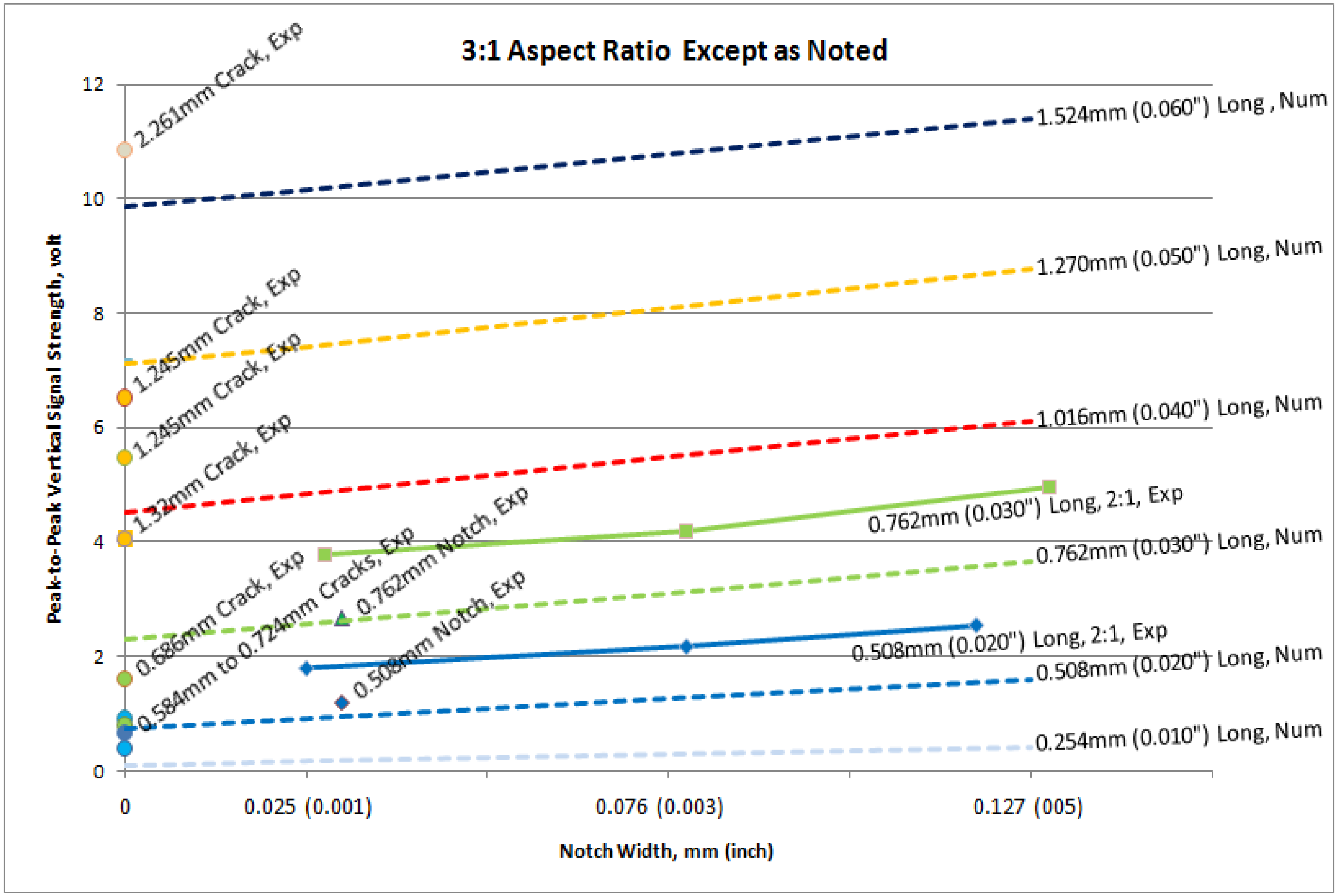


IN100 and Inconel 718 Notch Exp and Numerical Data

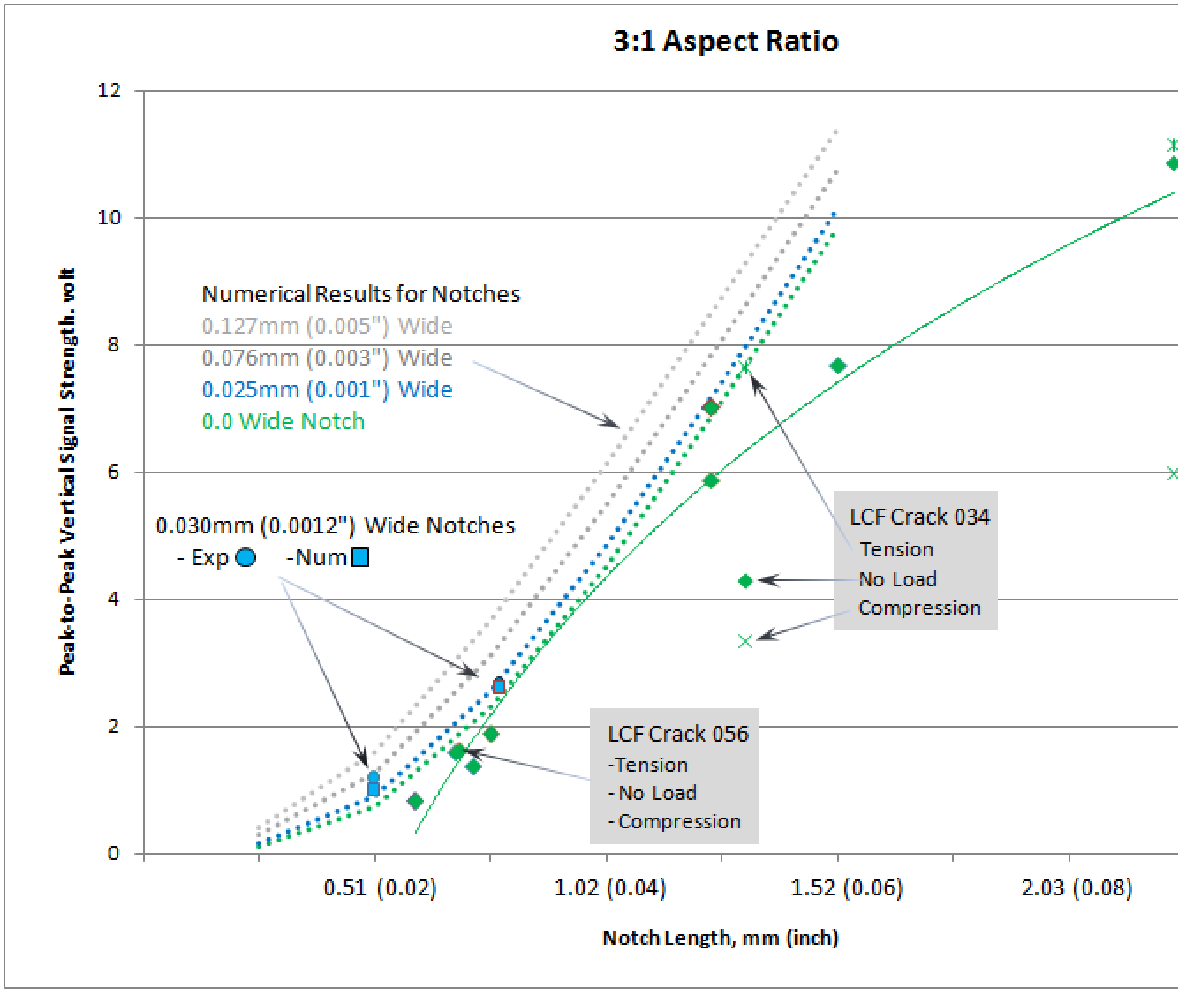


- The numerical model does a good job of capturing the notch width effect and the difference in conductivity between the two alloys.
- The signal change due to crack length change is slightly over estimated.

Numerical and Experimental Results for Inconel 718 Notches and Cracks



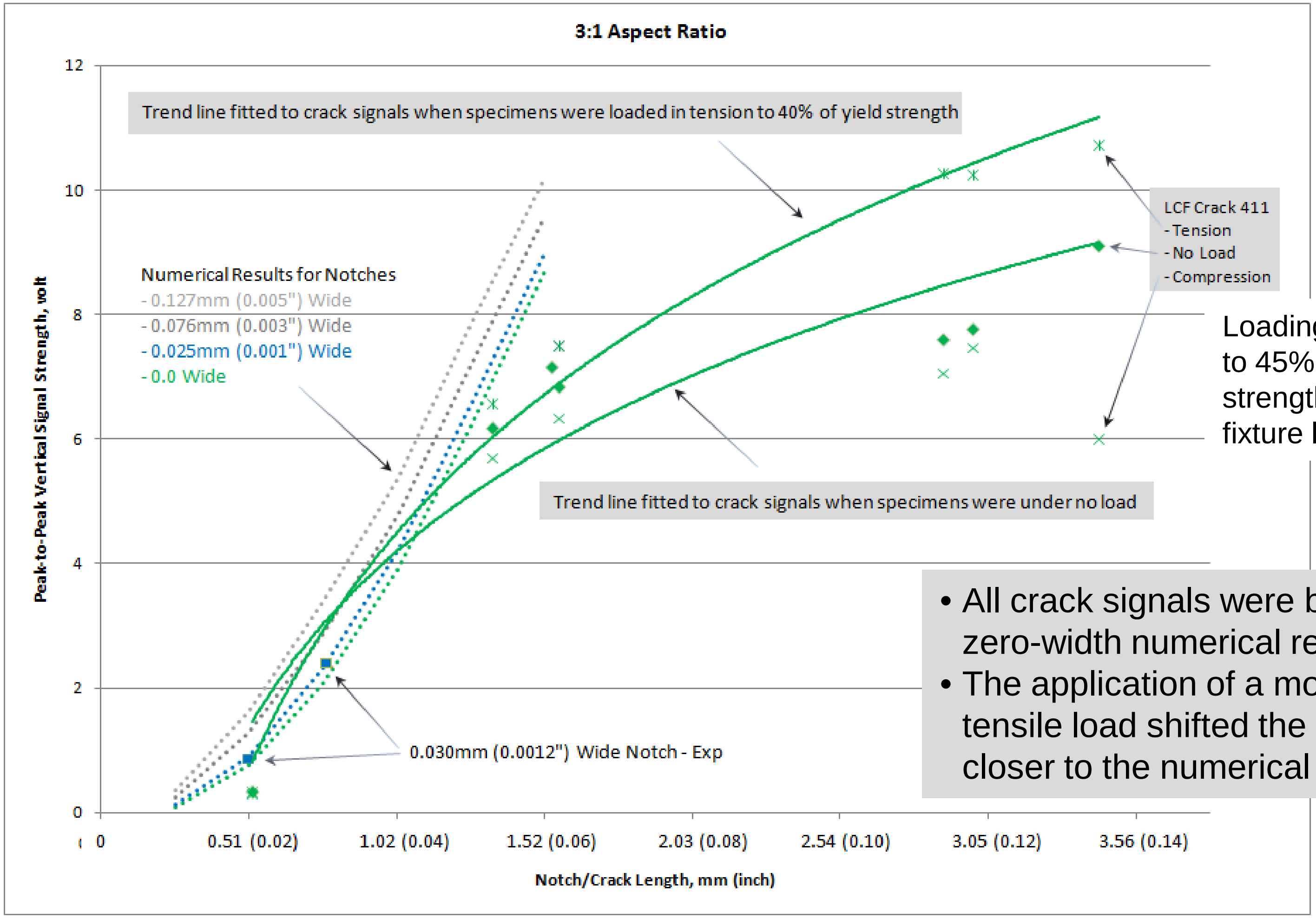
Inconel 718 Results as a Function of Notch/Crack Length



Loading limited to 5% of yield strength due to fixture limitations

- Fair agreement was seen between some crack signals and the zero-width numerical results.
- Main outlier was brought in line with application of a small tensile load.

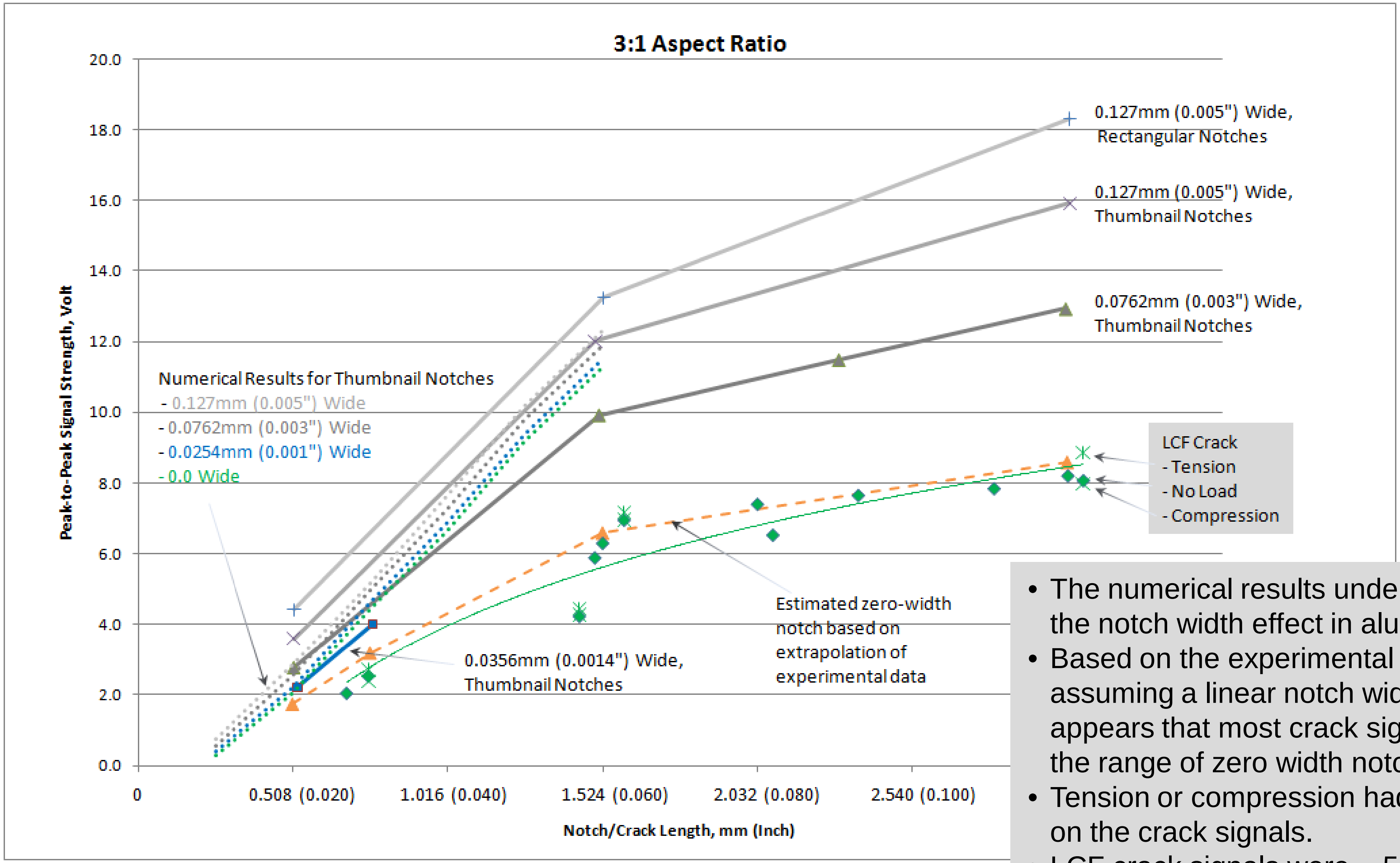
Ti 6-4 Results as a Function of Notch/Crack Length



Loading limited to 45% of yield strength due to fixture limitations.

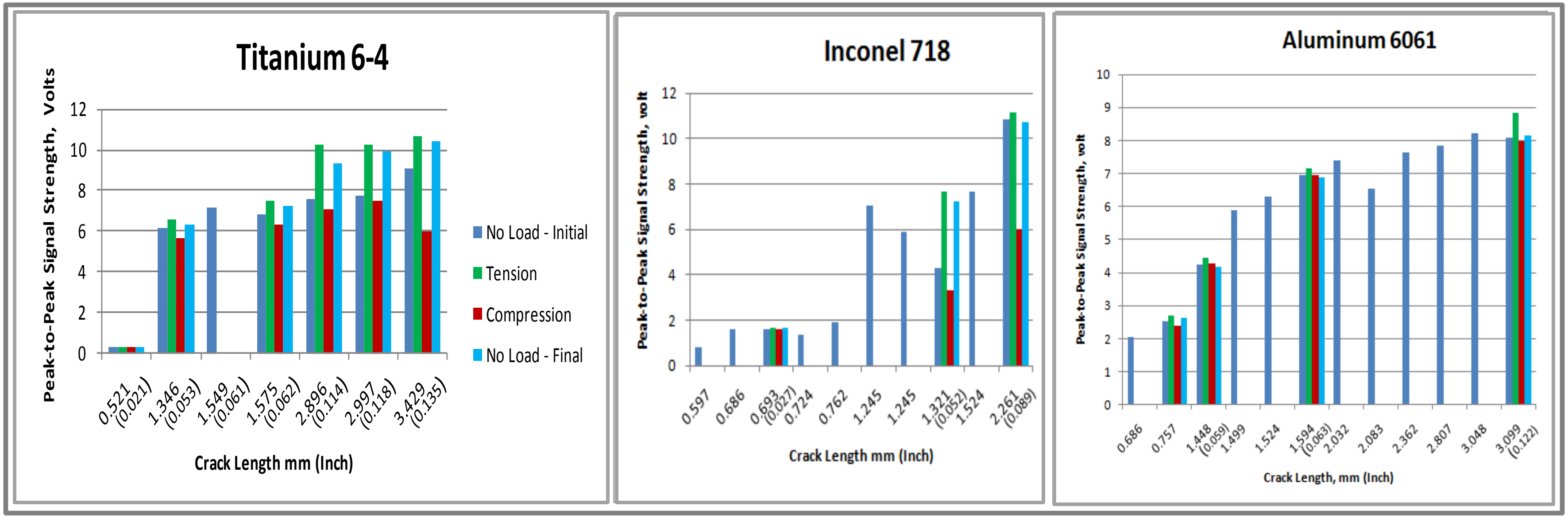
- All crack signals were below the zero-width numerical results.
- The application of a moderate tensile load shifted the trend line closer to the numerical results.

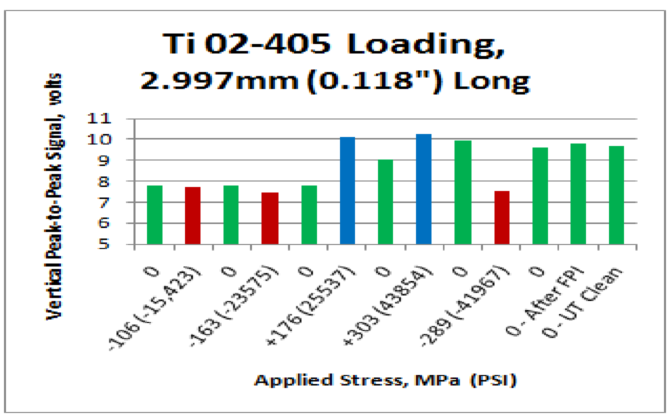
Al6061 Results as a Function of Notch/Crack Length



- The numerical results underestimate the notch width effect in aluminum.
- Based on the experimental data and assuming a linear notch width effect, it appears that most crack signals are in the range of zero width notch.
- Tension or compression had little effect on the crack signals.
- LCF crack signals were ~ 50% lower than 0.005" wide notches and ~35% lower than 0.003" wide notches.

Comparison of Loading Effects





- Tension generally produced some signal increase and compression some decrease for all three material.
- The loading effects were much larger in Ti and IN.
- In both Ti and IN, signals did not return to initial baseline no-load level after the tensile load was removed but remained near that of the loaded signal.
- Compression loading after tension produced a minor reduction in the no-load signal.

Summary

- The effect of discontinuity width and loading on EC signals has been evaluated for titanium, Inconel and aluminum alloys.
- For Ti and Inconel
  - Numerical calculations provided a reasonable estimate of zero-width discontinuity signals.
  - Signals from low-cycle fatigue cracks generally fall below the estimated zero-width signal. Minor tensile loading improved the agreement in IN; greater loading was required for Ti.
  - Once loaded in tension, the crack signals remained above initial baseline levels.
- For Aluminum
  - The numerical algorithm did not provide a good estimate of zero-width discontinuity signals.
  - A linear extrapolation of the experimental data from notches was used to estimate the zero-width notch signal and most crack signals fell close to the estimated zero-width notch signals.
  - Tension and compression had a minor effect on the crack signals.

Follow-On Work

- Evaluate different frequencies…especially a lower frequency for aluminum.
- Improve numerical model to better estimate the notch width effect for aluminum and high conductivity materials.
- Extend model results beyond 0.060 inch.
- Continue to investigate reasons for signal changes (or lack thereof) due to tension and compression.

EC Edge Crack Detection and its Modeling

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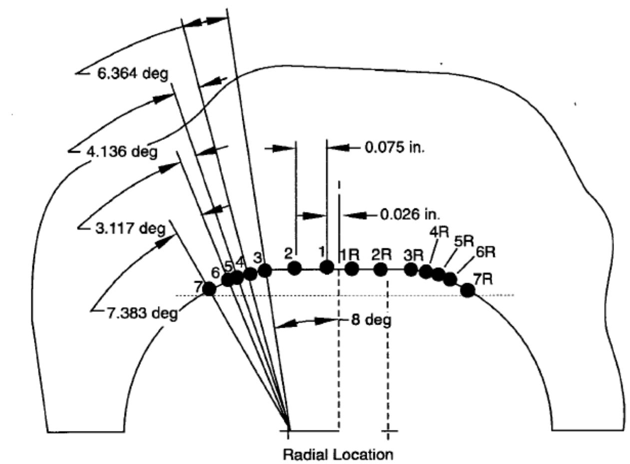
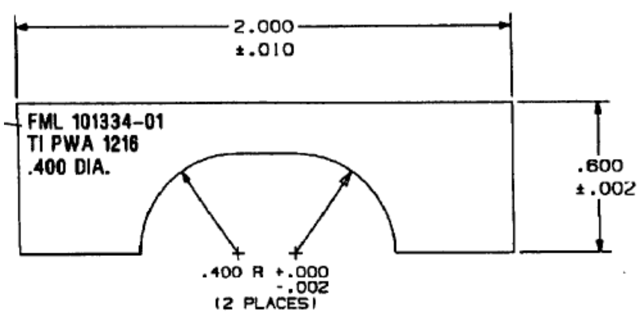
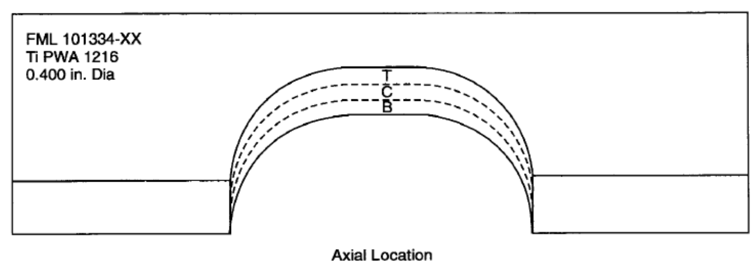
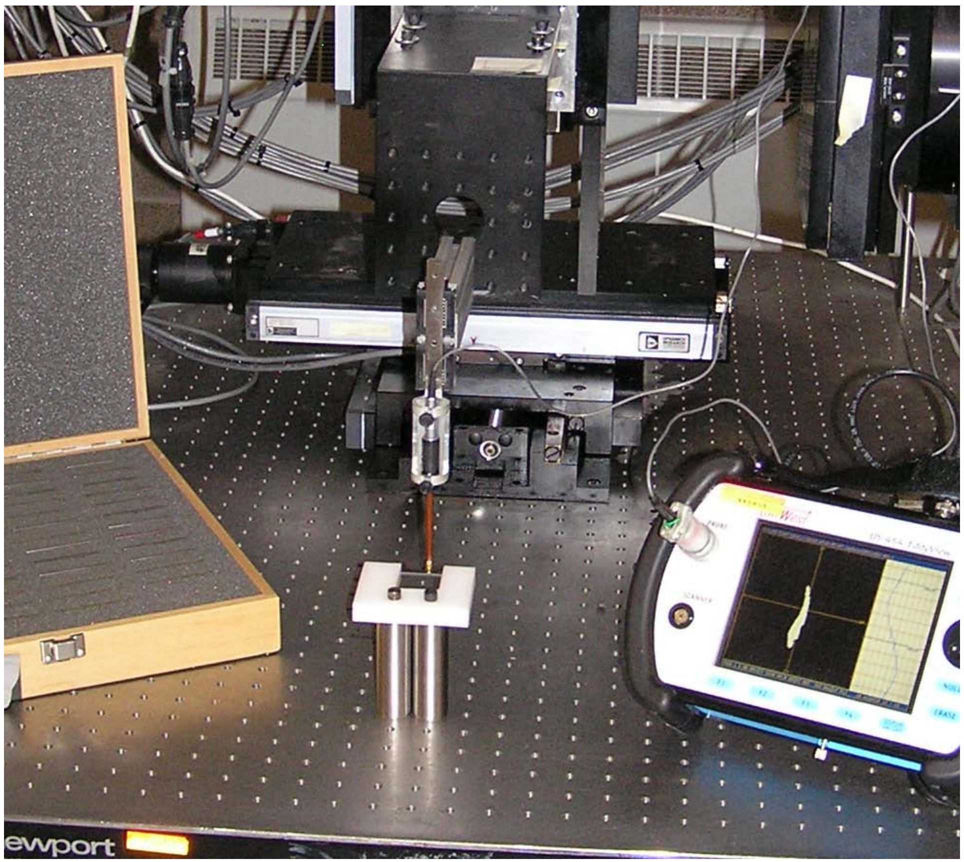
Edge Crack Samples

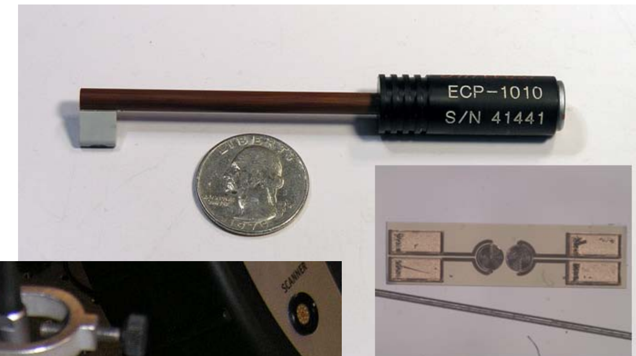




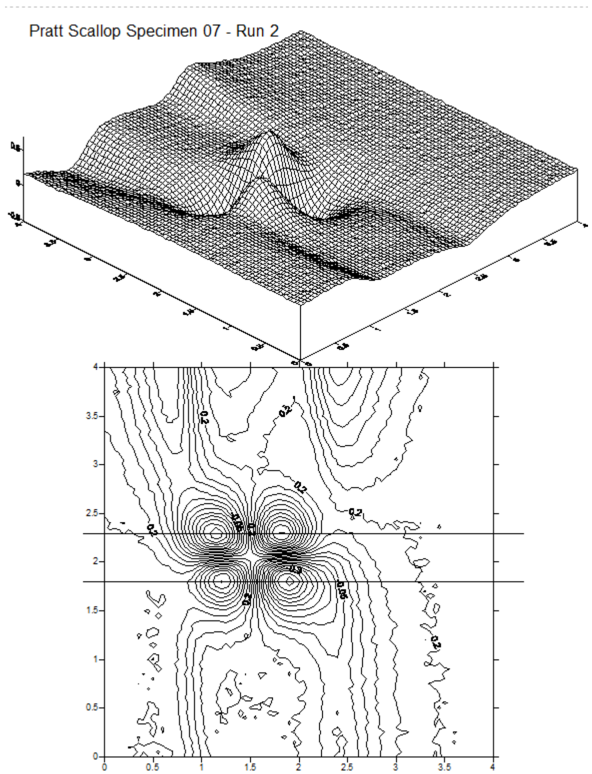


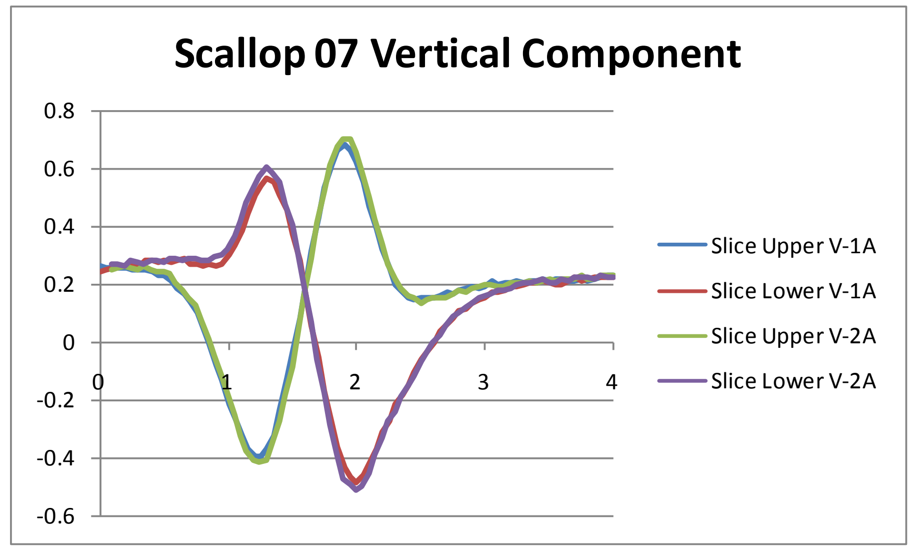
Edge Crack Detection Apparatus with "Flag" Probe





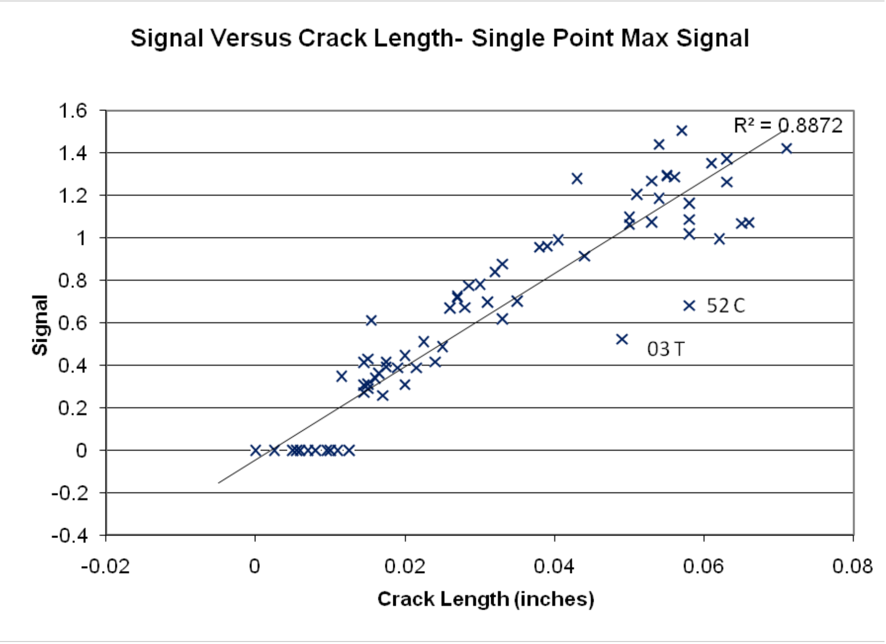
Typical Raster Scan Data

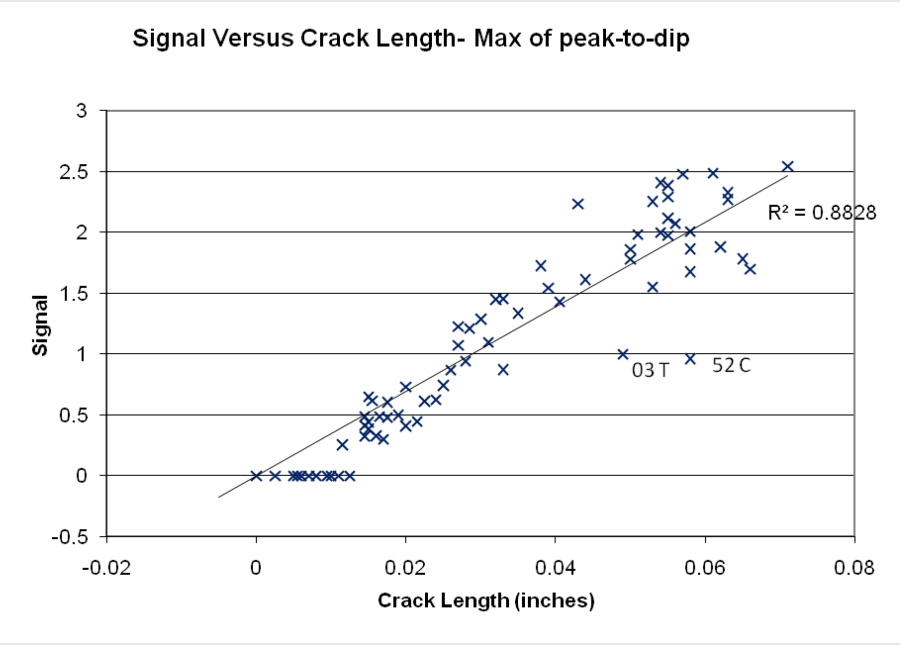




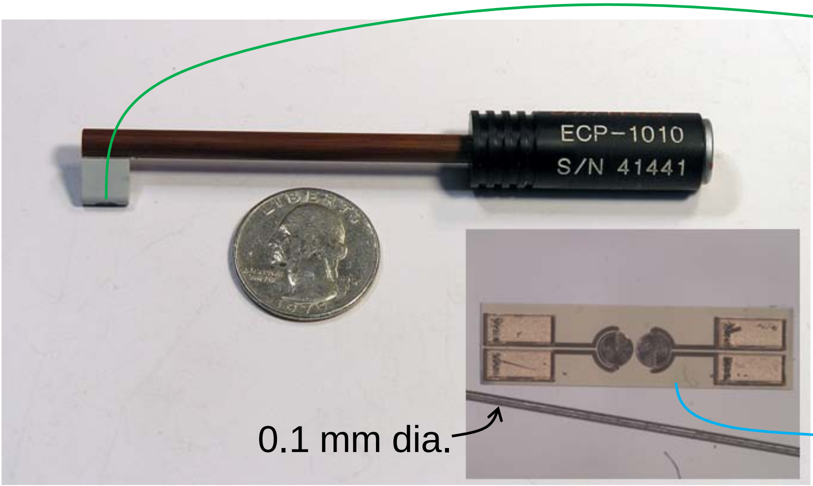
Example of the scan data plotted as both a wire mesh diagram and contour plot (left) and the resulting line plots of the slices for the vertical portion of the signal. Note the slice data for two scans is shown to demonstrate the measurement repeatability.

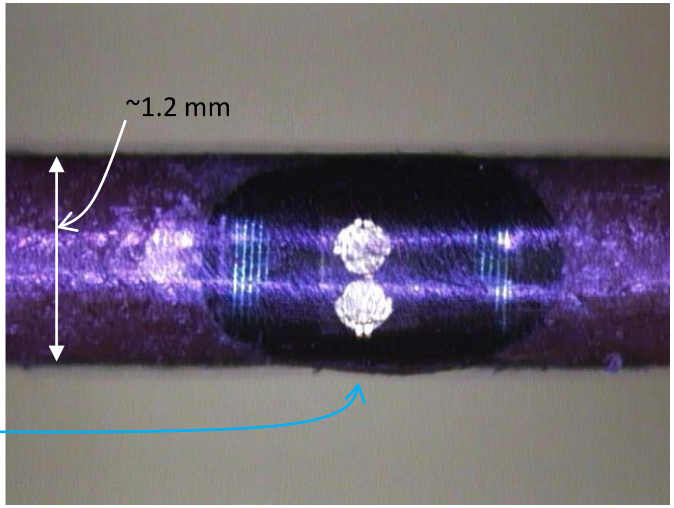
Data to be used for POD Analyses

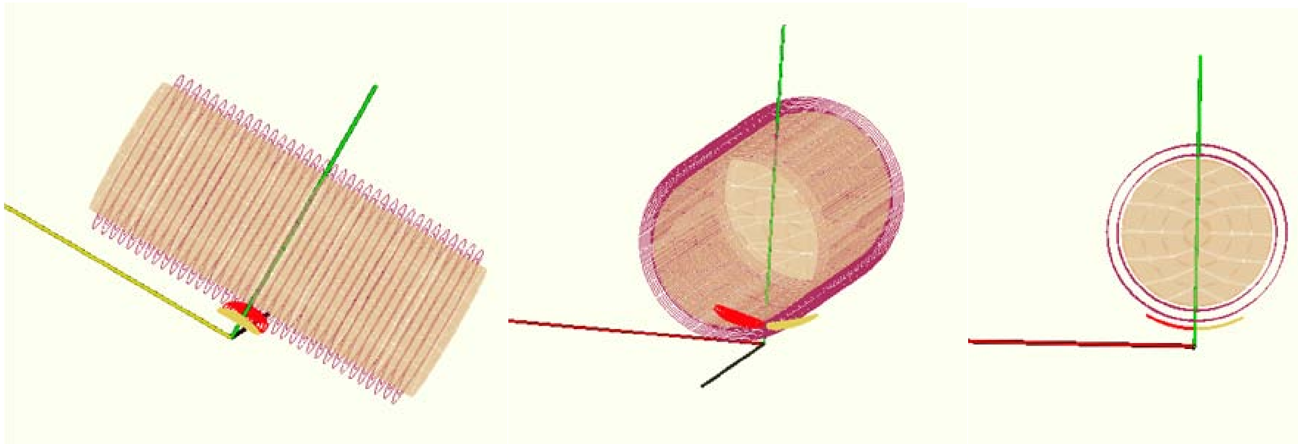




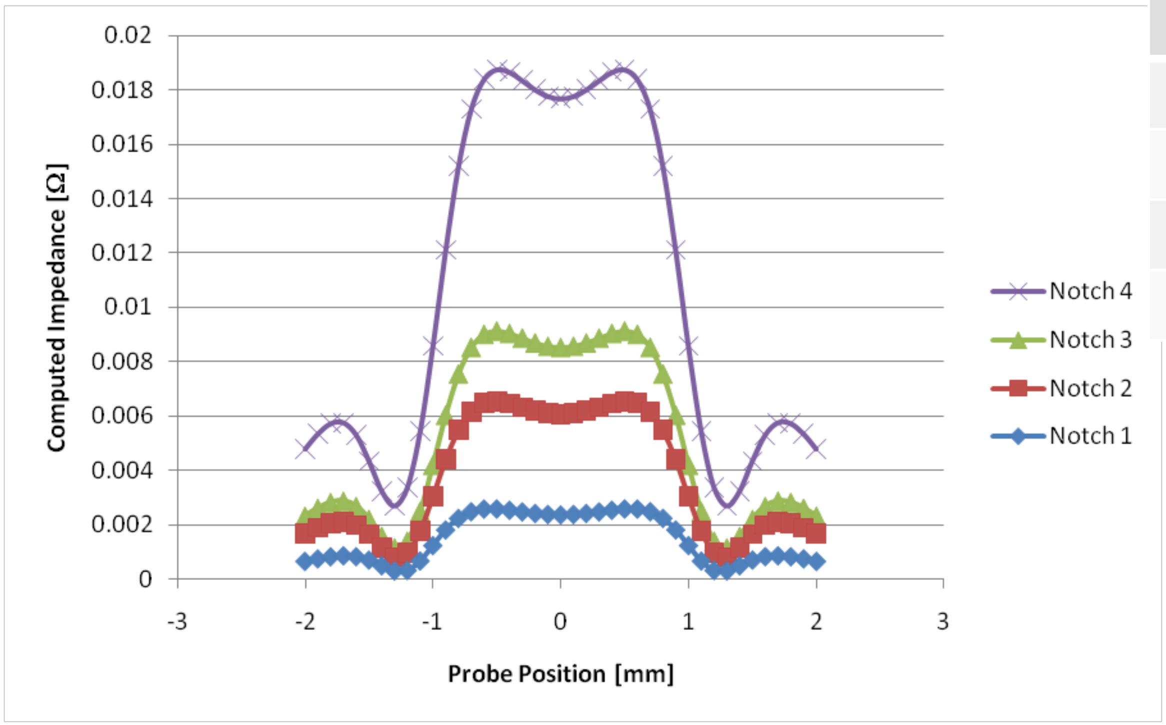
“Flag” Probe Characterization & Modeling







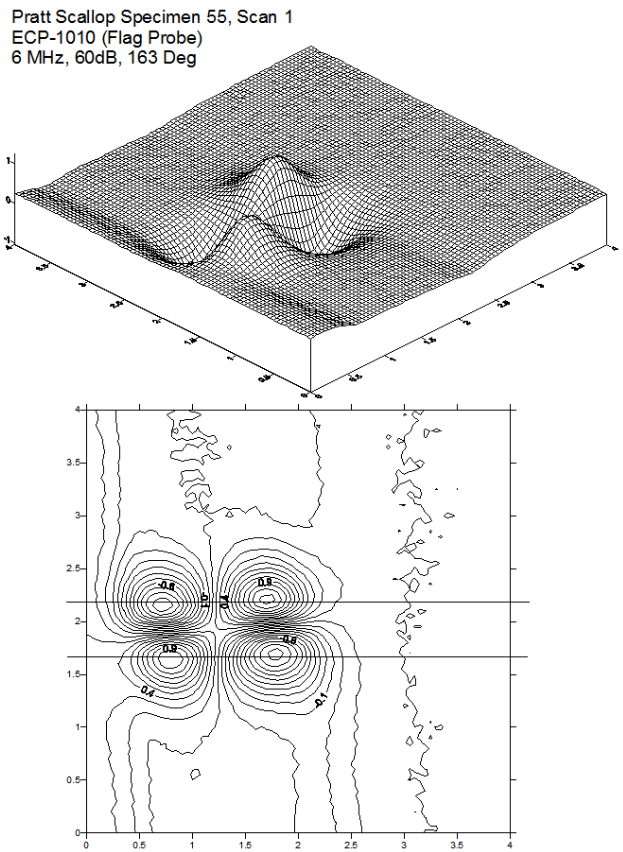
Computed Notch Signals, Preliminary

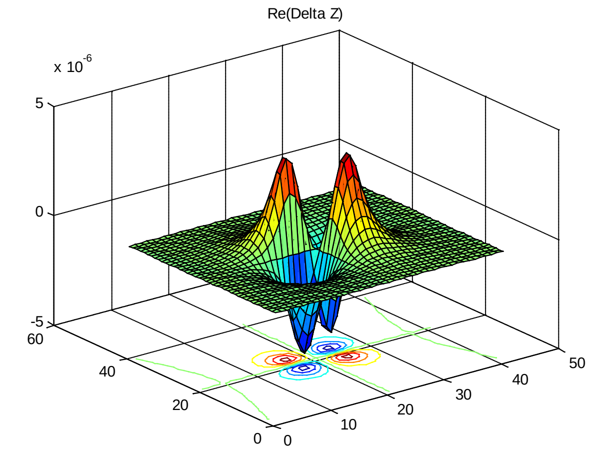


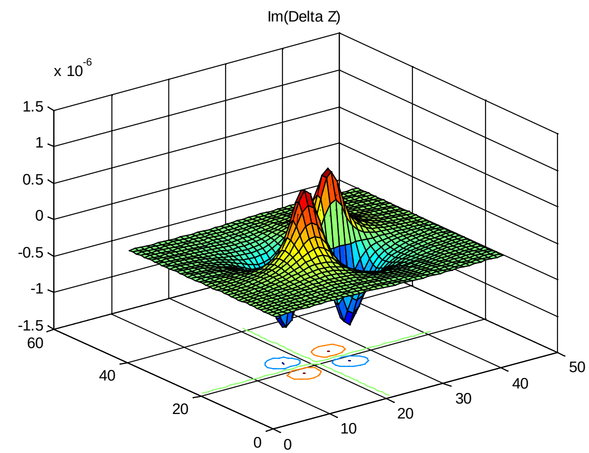
Notch	L (mil)	D (mil)	W (mil)
4	32	16	4
3	21	11	4
2	18	9	4
1	11	6	4

$f=6$ MHz
$\sigma=0.748$ MS/m
$Z_{lift\text{-}off}=0.127$ mm

4-prong C-Scan Data: Expt. & Model







Follow-On Work

- Detailed comparisons between experiment and theory will follow.