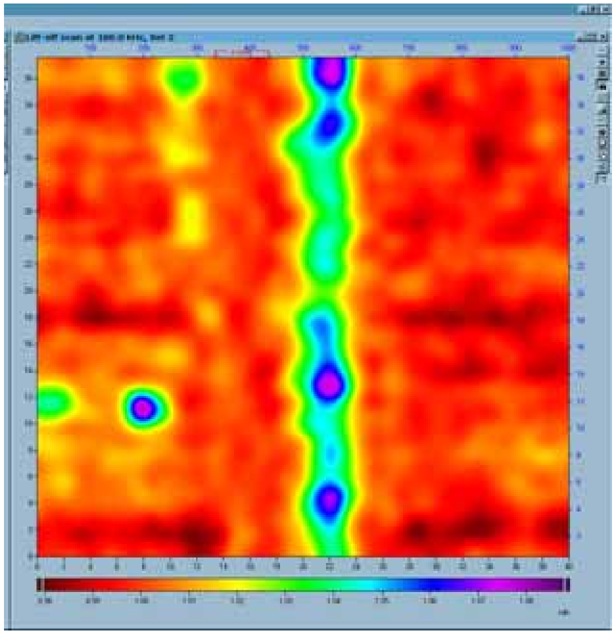

Friction Stir Weld Inspection using MWM Eddy-Current Sensor Arrays

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and Dr. Neil Goldfine

JENTEK Sensors, Inc.

Brent Christner

Eclipse Aviation

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June 11, 2003

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Overview

- MWM®-Array conductivity and effective lift-off mapping for Friction Stir Weld (FSW) inspection
  - Butt welds and lap joint welds
  - Similar metal and dissimilar metal welds
  - Lack of penetration (LOP) for butt welds
  - Anomalies associated with abnormal welding conditions

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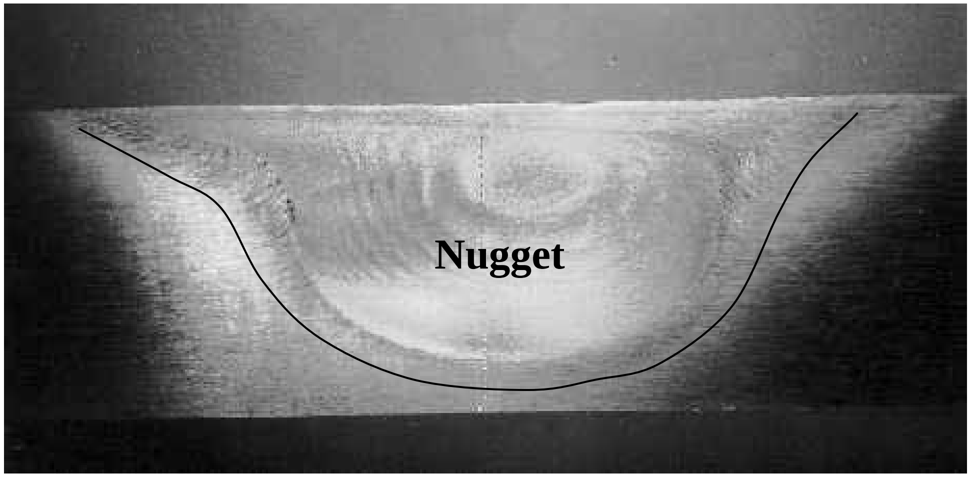
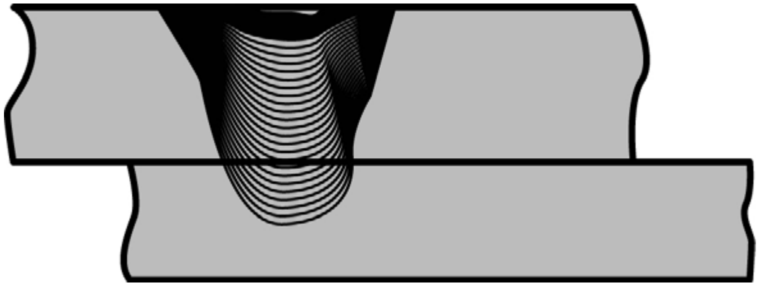
Friction Stir Weld Geometries

Butt Weld



Lap Joint



JENTEK Instrumentation and MWM-Arrays

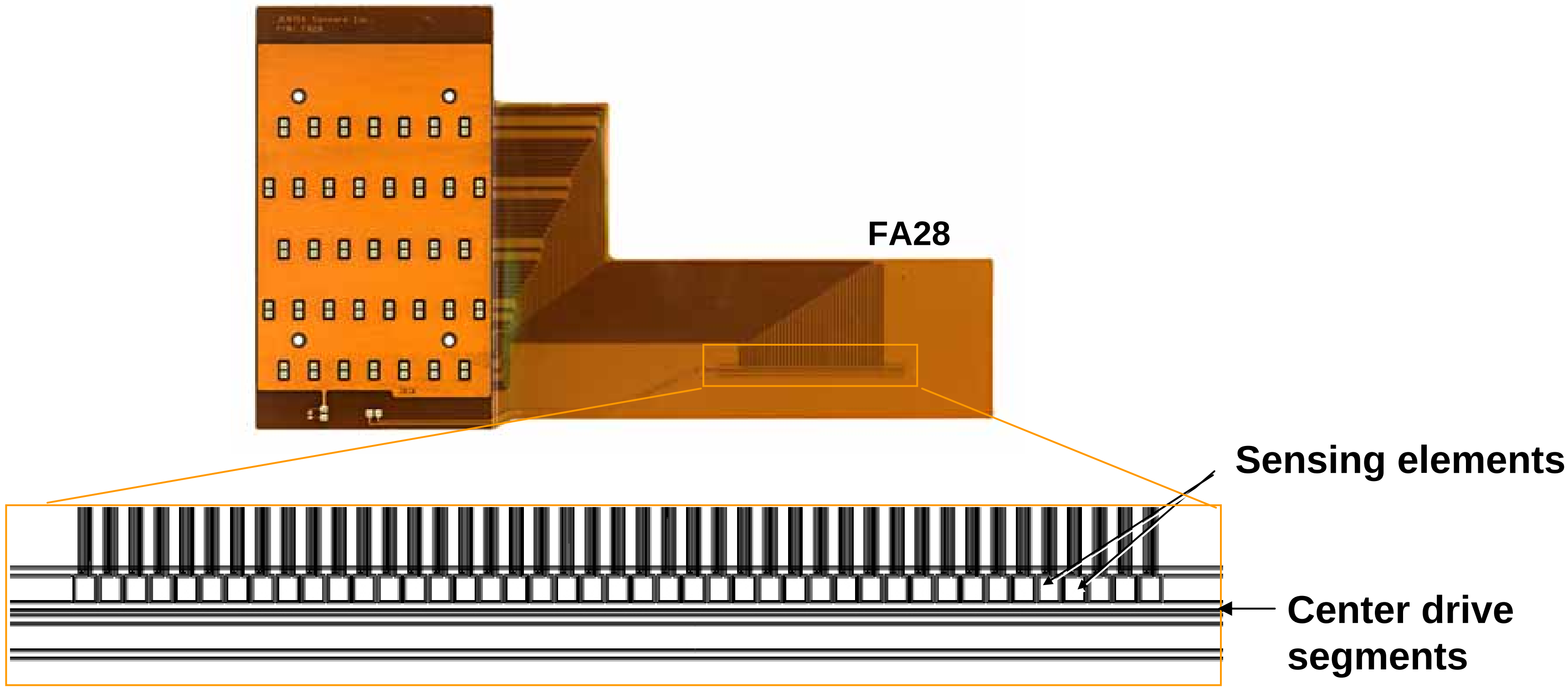
- Conformable MWM-Arrays
- Multi-frequency measurements (1 kHz to 40 MHz)
- Bi-directional measurements
- Multi-Channel Instrumentation
- Multiple unknown algorithms
- GridStation® software

7-Channel System;
Available up to 39 channels

MWM-Array Probe and
Interchangeable Probe Tips

MWM-Array Probe for
Manual Scanning

Photo and Detail of JENTEK MWM-Array

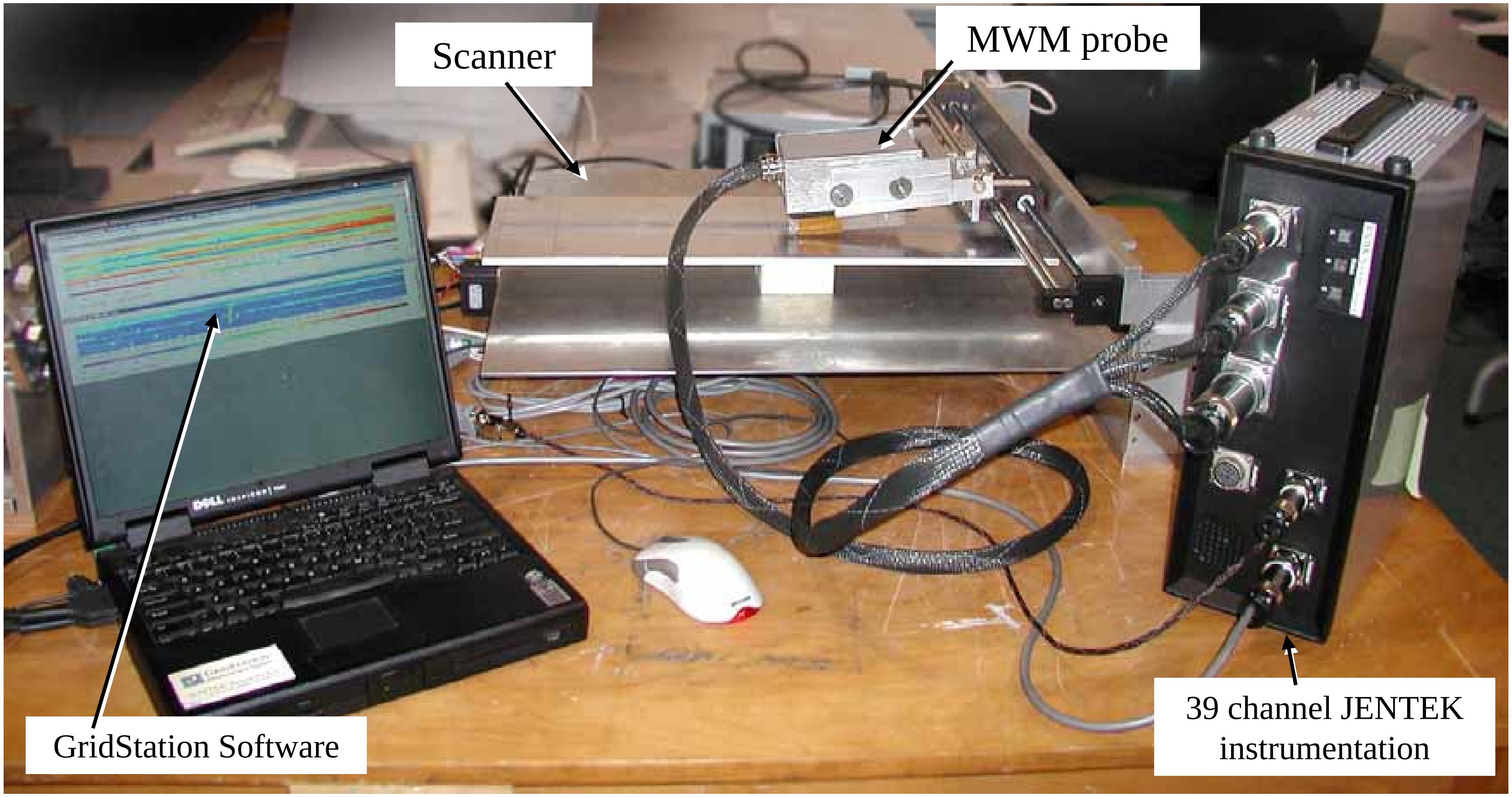


- Spacing between the sensing elements is 1.02 mm

MWM-Array Inspection of FSWs – Butt Welds

- Similar and dissimilar Al alloy welds
- LOP detection and characterization
- Blind test and control panels

Setup of the JENTEK GridStation system and two-dimensional scanner used for the FSW inspection



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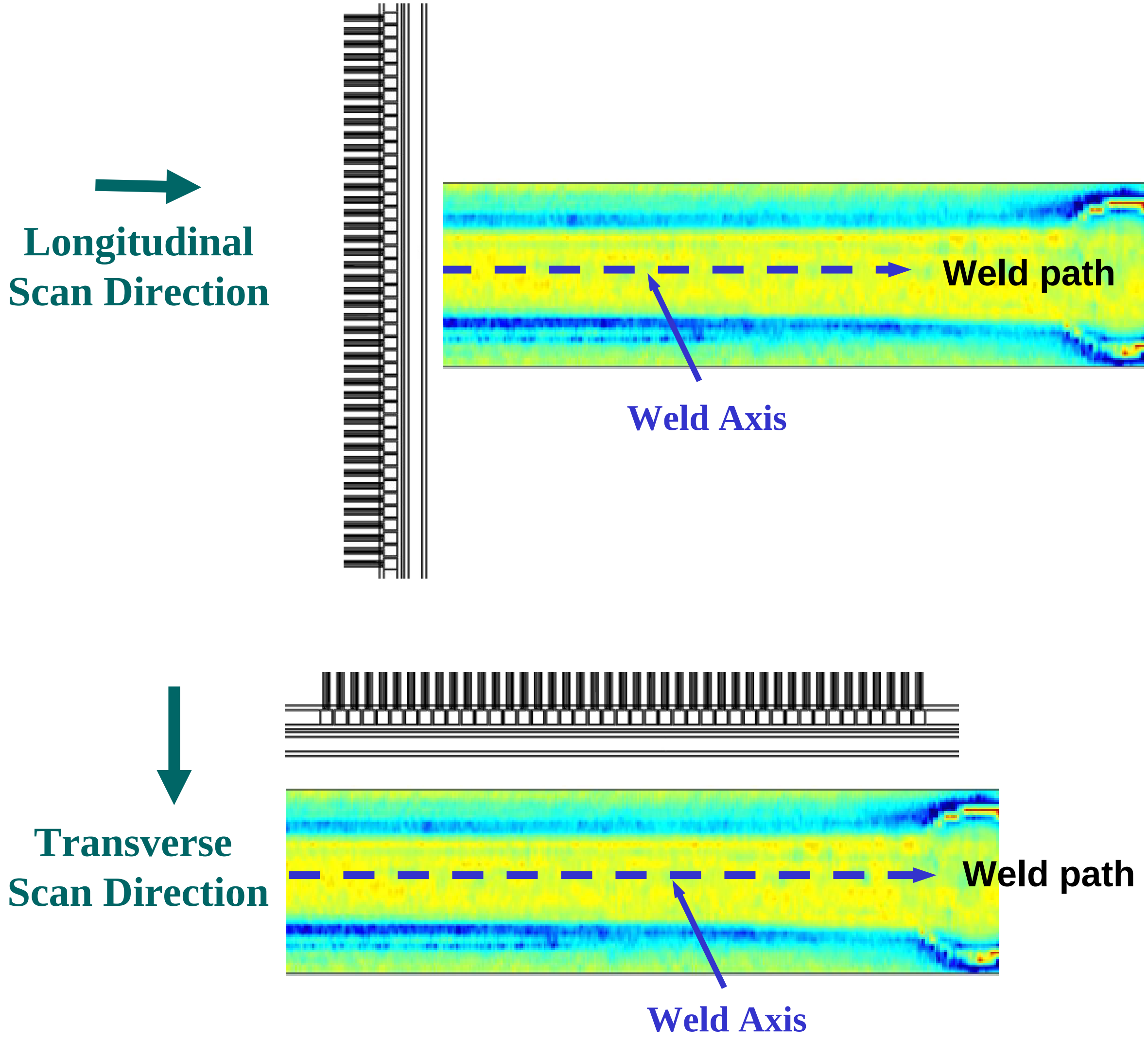
MWM-Array Orientations for Scanning of a Friction Stir Weld



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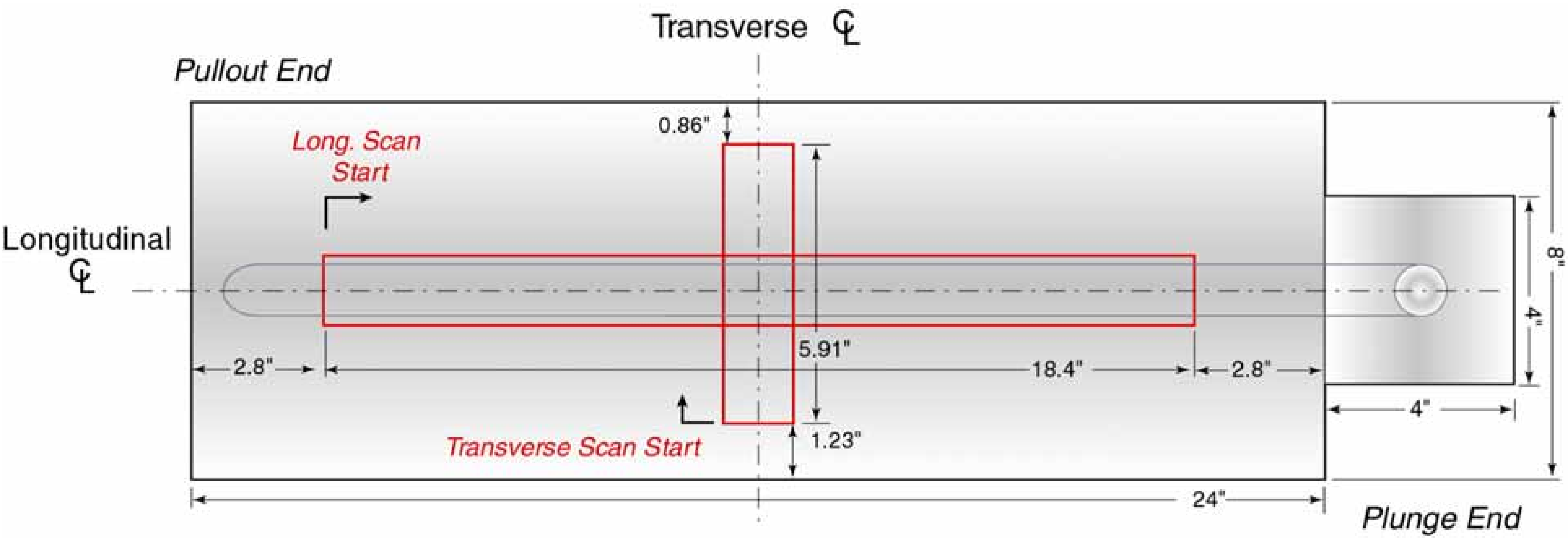
Schematic of the FSW panels used in a recent study

Coverage (in red) of the MWM-Array FA28 during scanning in the transverse and longitudinal directions



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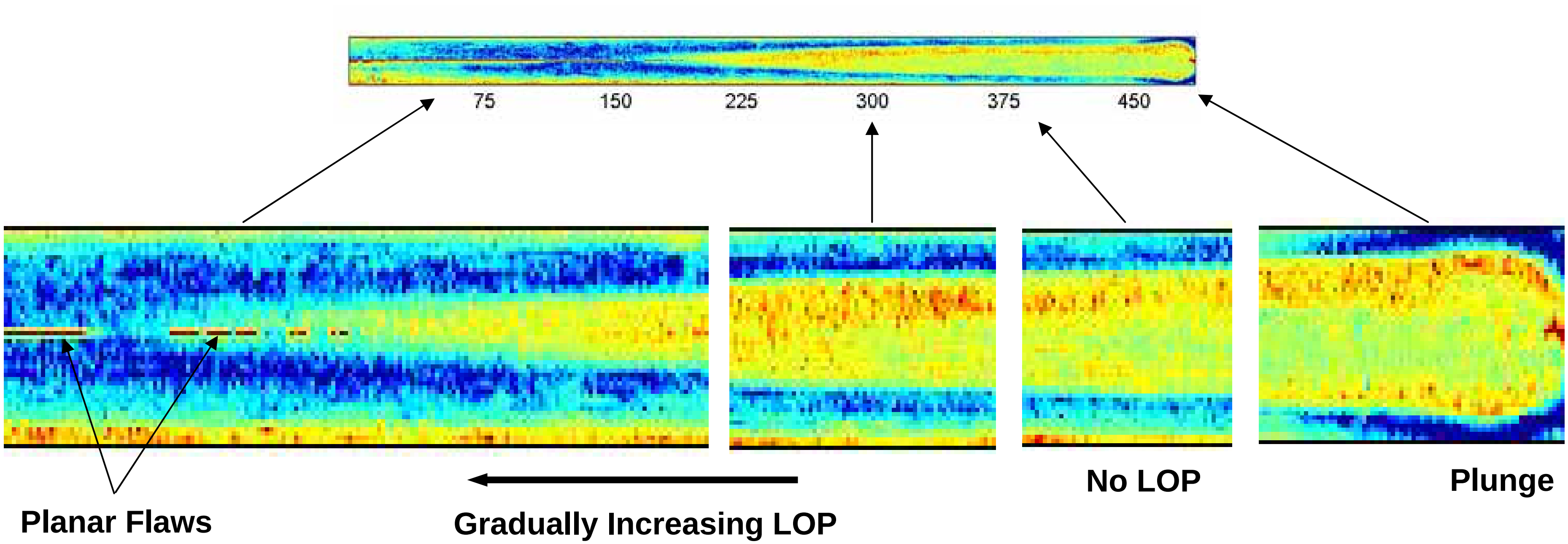
MWM-Array conductivity image of FSW in a blind test panel



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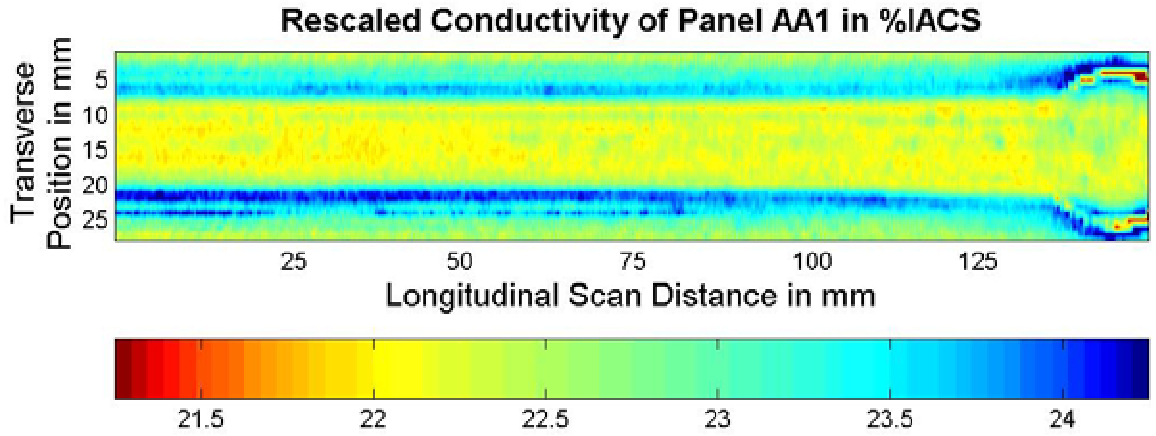
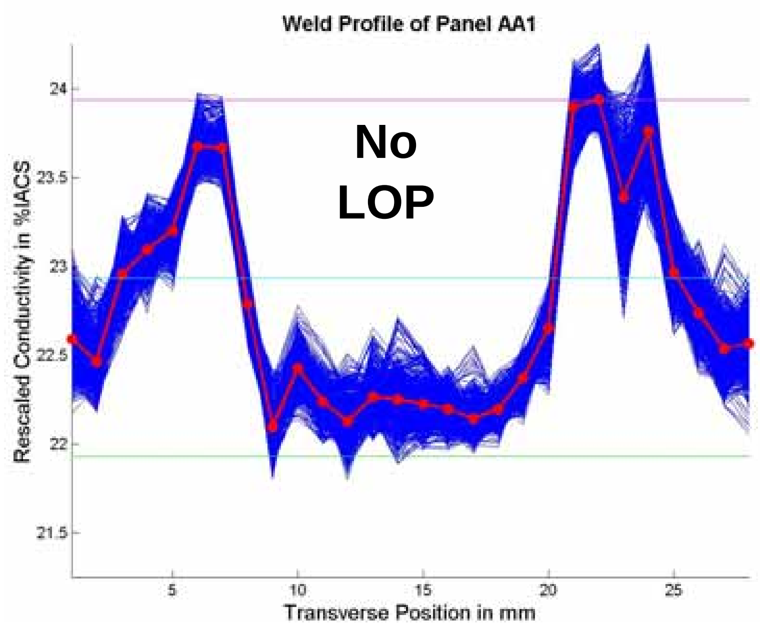
Conductivity image and profile for similar metal FSW





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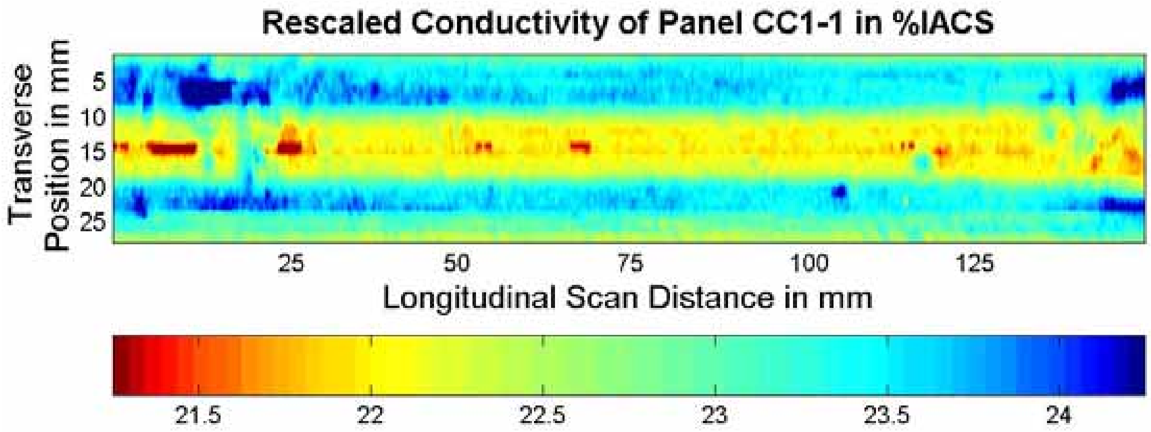
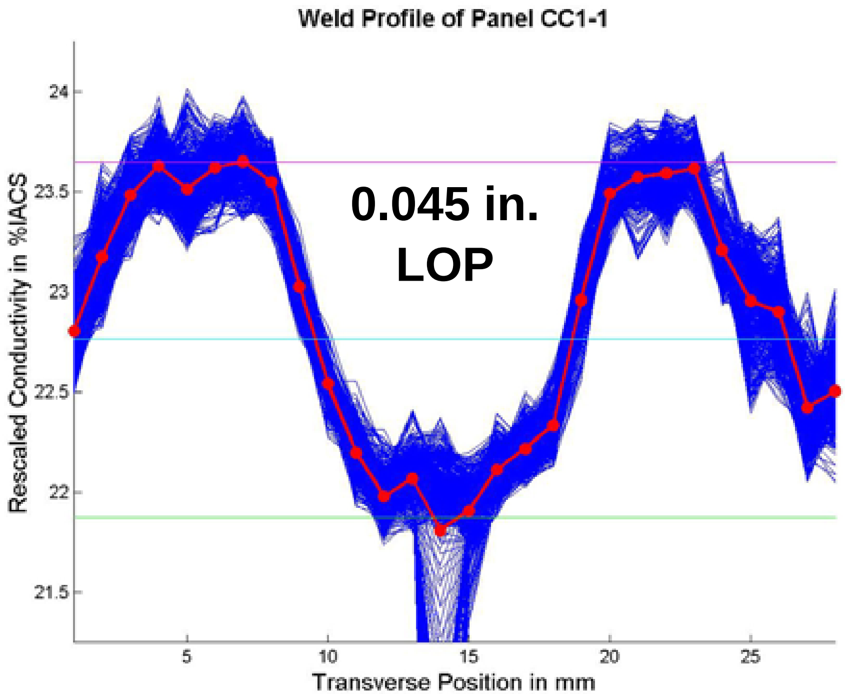
Conductivity image and profile for similar metal FSW





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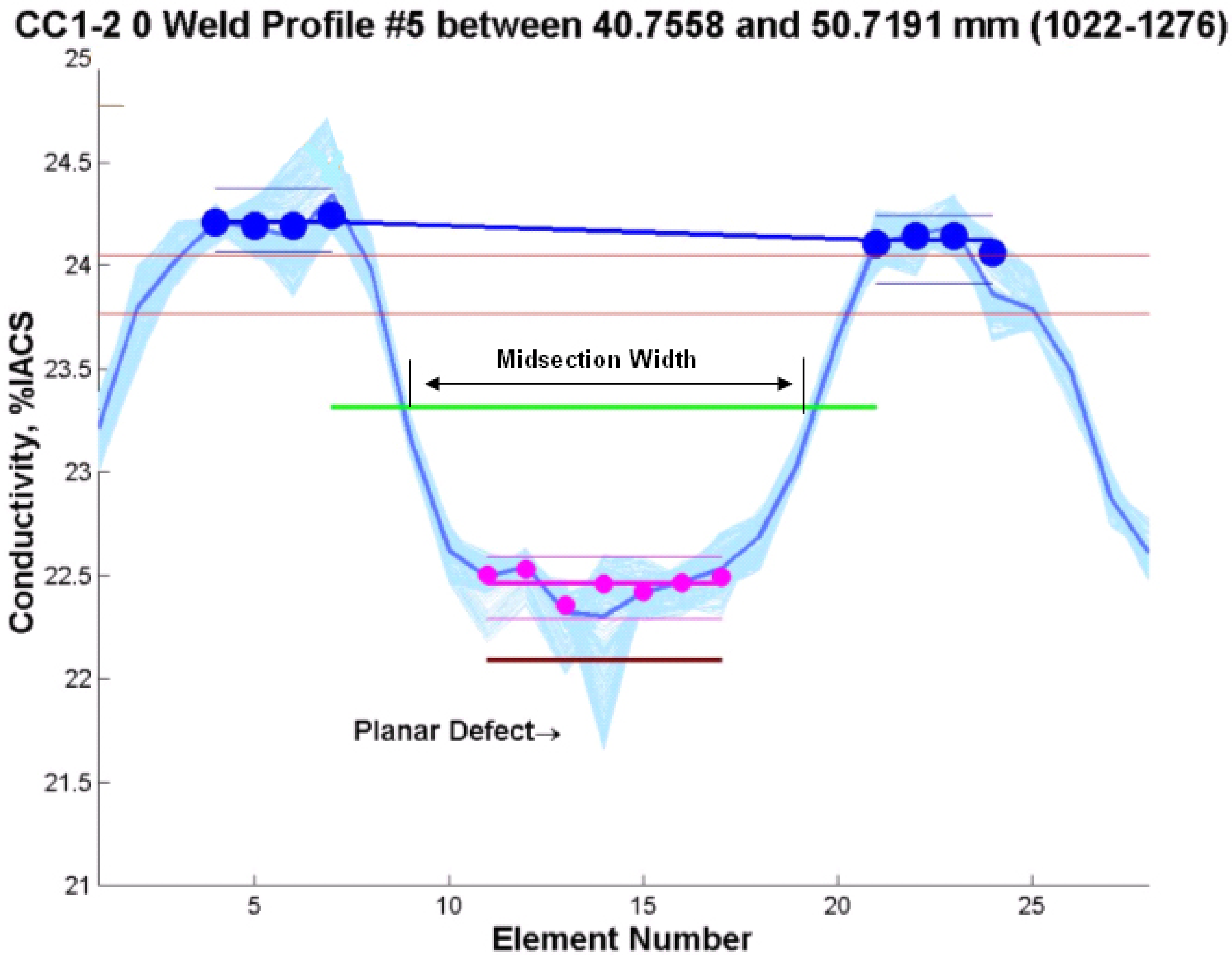
Conductivity profile schematically showing the midsection width definition for a similar metal FSW



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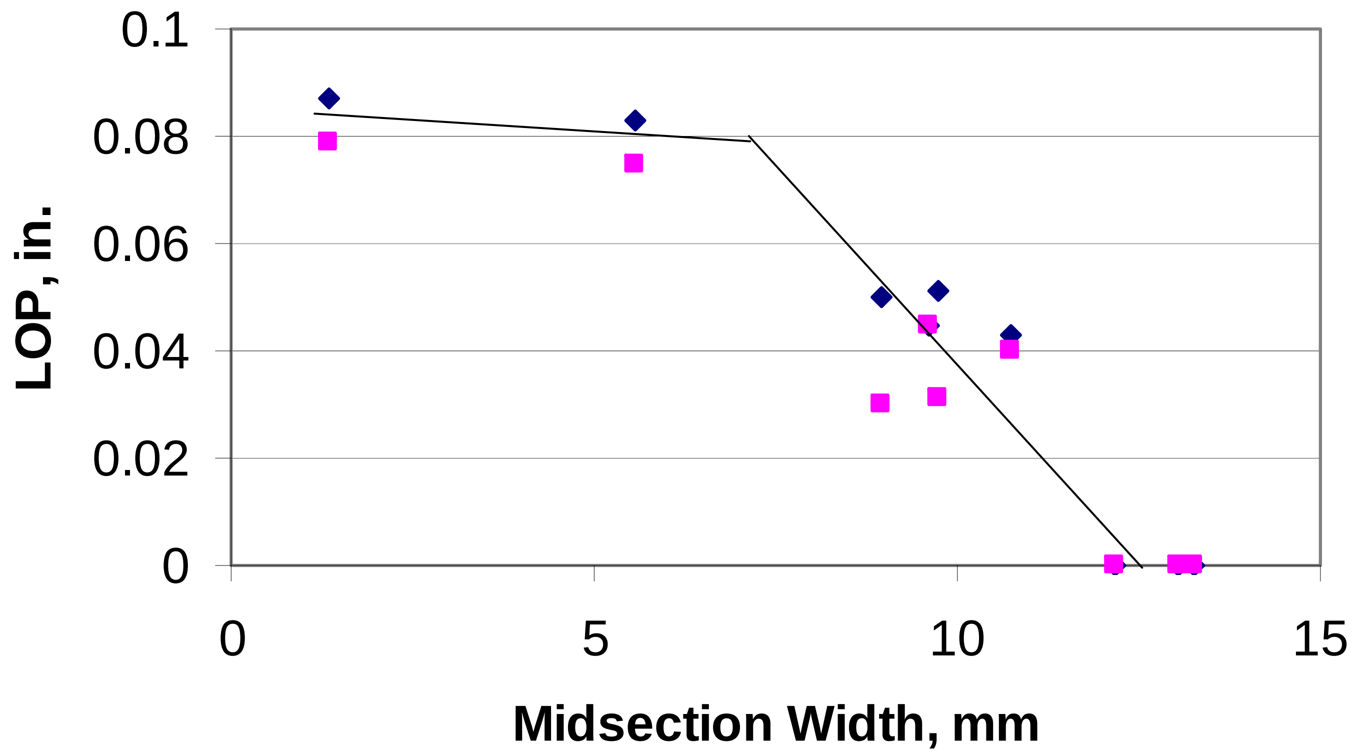
Correlation between the midsection width and LOP for similar metal FSWs



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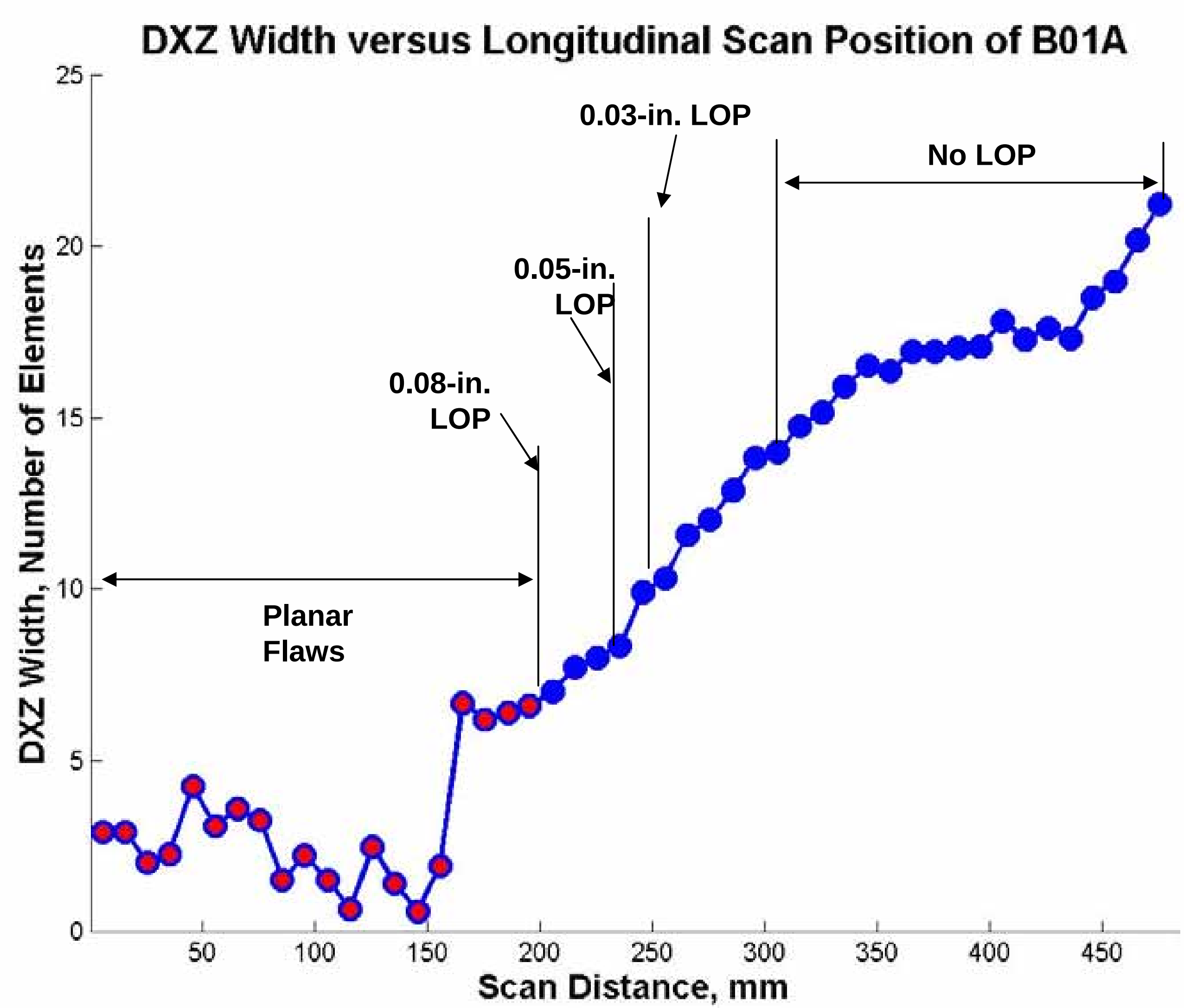
Midsection width along the similar metal "tapered" FSW



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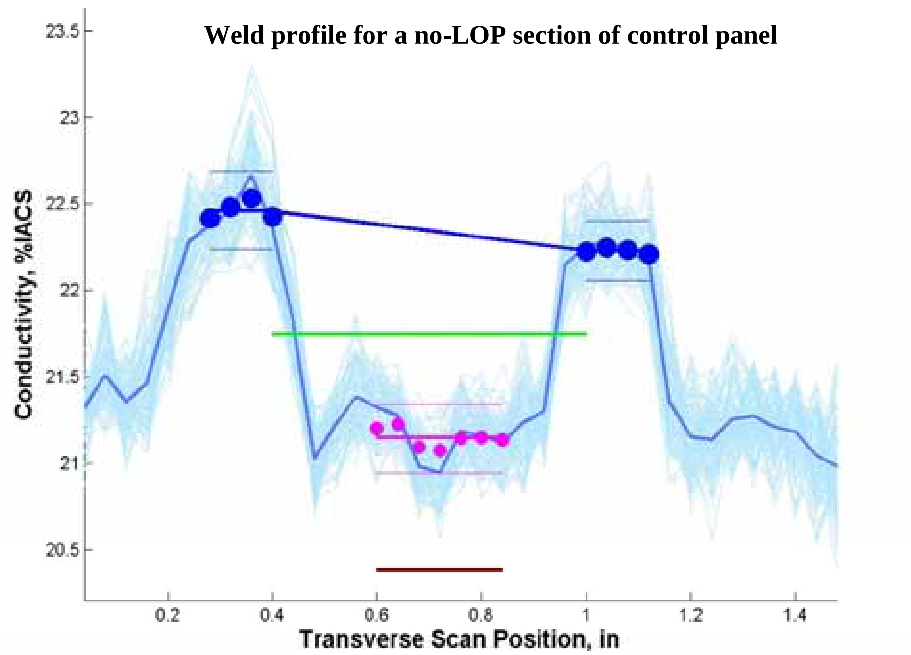
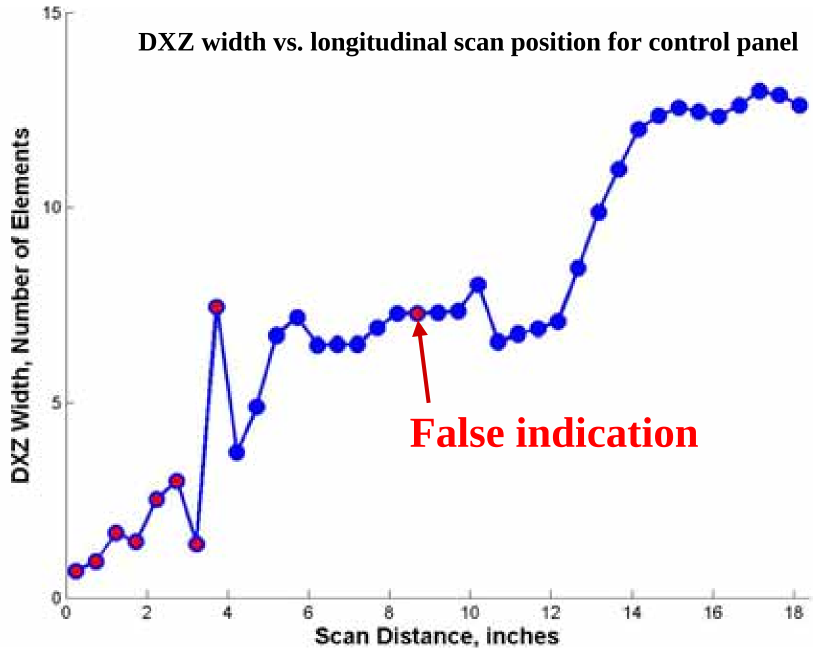
Automated algorithm developed by JENTEK output plots (left plot) showing the peak determination of the HAZ and the DXZ (green line) and planar defect (maroon line) cutoff values

The script determines the average width of the DXZ for windows, 0.4997" wide in this case, along the longitudinal scan and plots the results (right plot).





Notes: Regions of the scan containing planar defects are denoted by red. The unusually high width determined for the planar defect at the 4-in. position is an outlier. The planar defect detected at 8.5-in. position is false and is due to a local region of the DXZ with a reduced conductivity.

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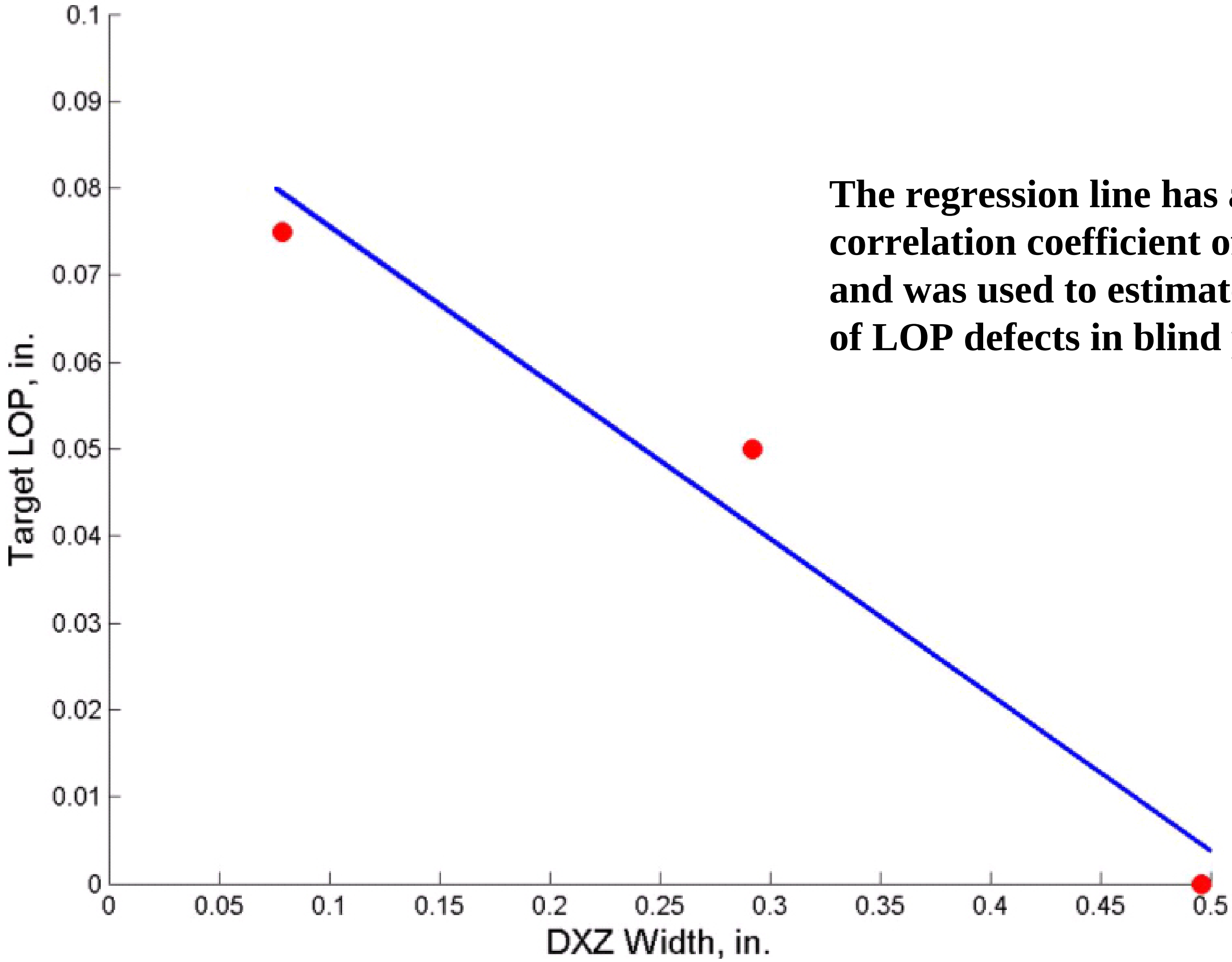
Plot of the target LOP of the three regions of the FSW of a control panel vs. the DXZ width determined by the algorithm developed by JENTEK using conductivity data from a longitudinal scan



The regression line has a correlation coefficient of –0.98 and was used to estimate the size of LOP defects in blind panels

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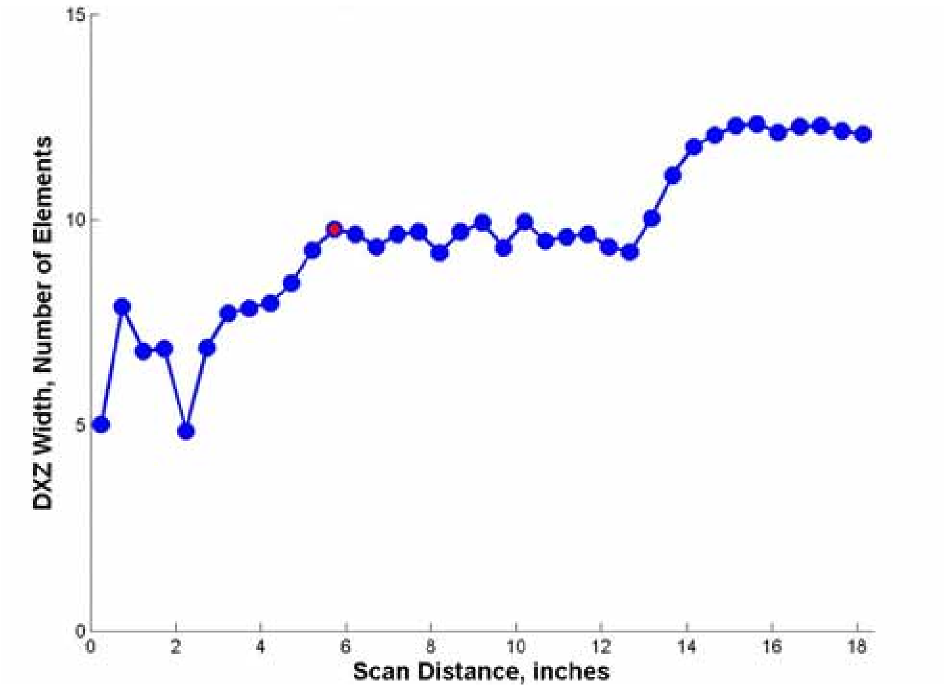
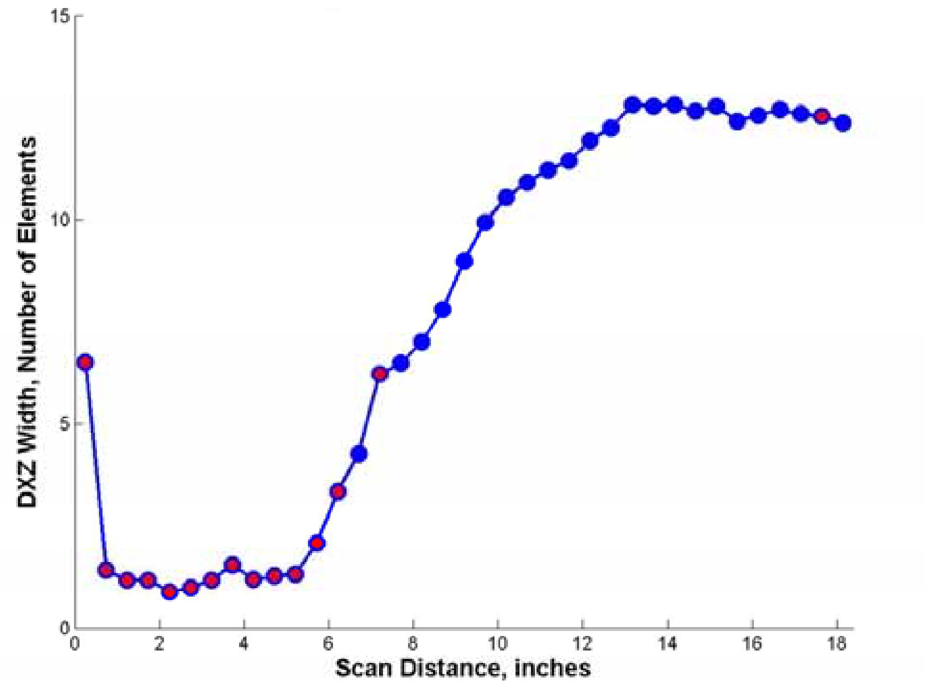
The DXZ width vs. scan position in blind test panels

DXZ Width vs. Longitudinal Scan Position in Panel 1



DXZ Width vs. Longitudinal Scan Position in Panel 2



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MWM-Array Inspection of FSWs – Lap Joints

- Al alloy panels
- Nominally good sections produced by a qualified weld procedure
- Sections welded under conditions significantly different from nominal
- Tool rotation and tool speed

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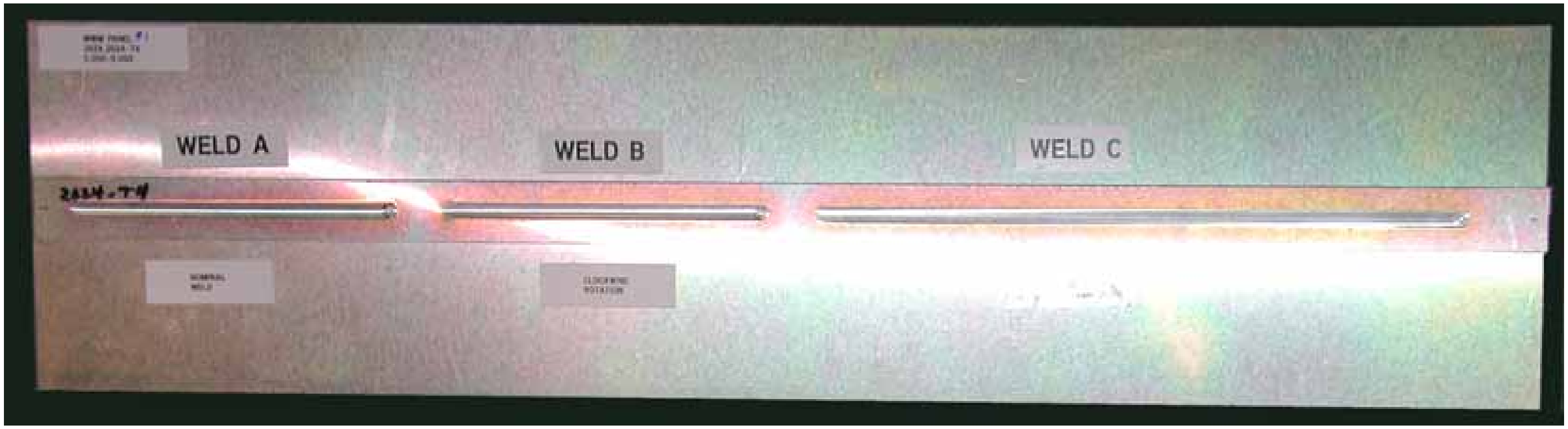
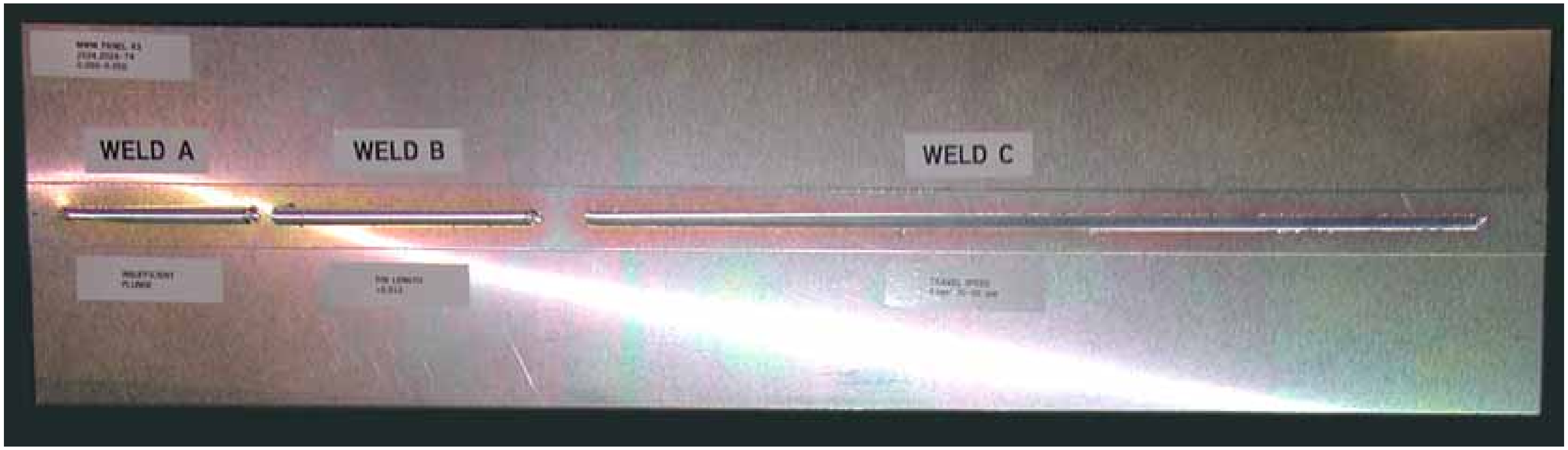
FSW Lap Joint Panels supplied by Eclipse Aviation



Panel #1



Panel #3

ECLIPSE AVIATION

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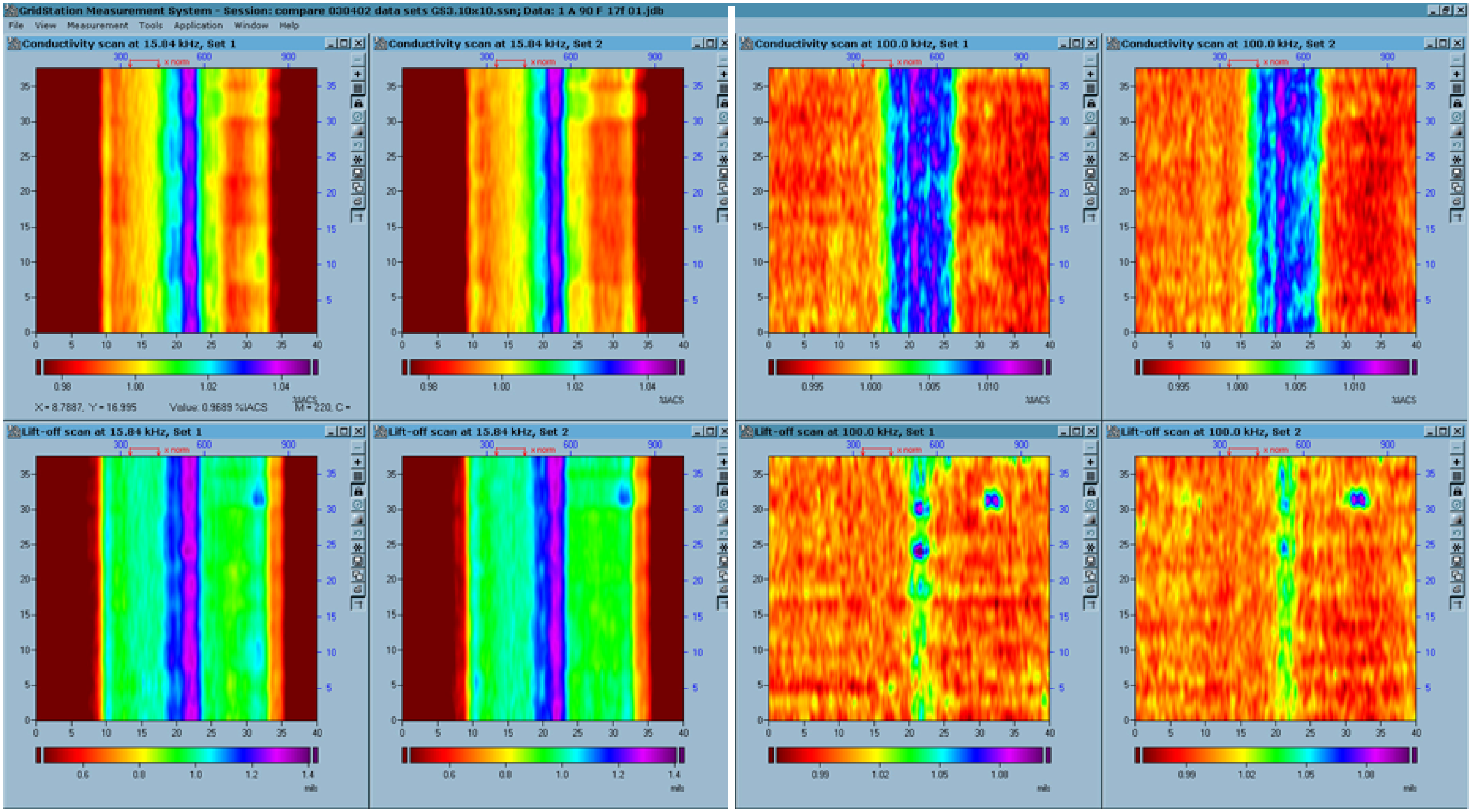
Effective conductivity and lift-off images at 15.84 and 100 kHz for weld A of Panel #1 produced by nominal welding conditions



15.84 kHz **100 kHz**

ECLIPSE AVIATION

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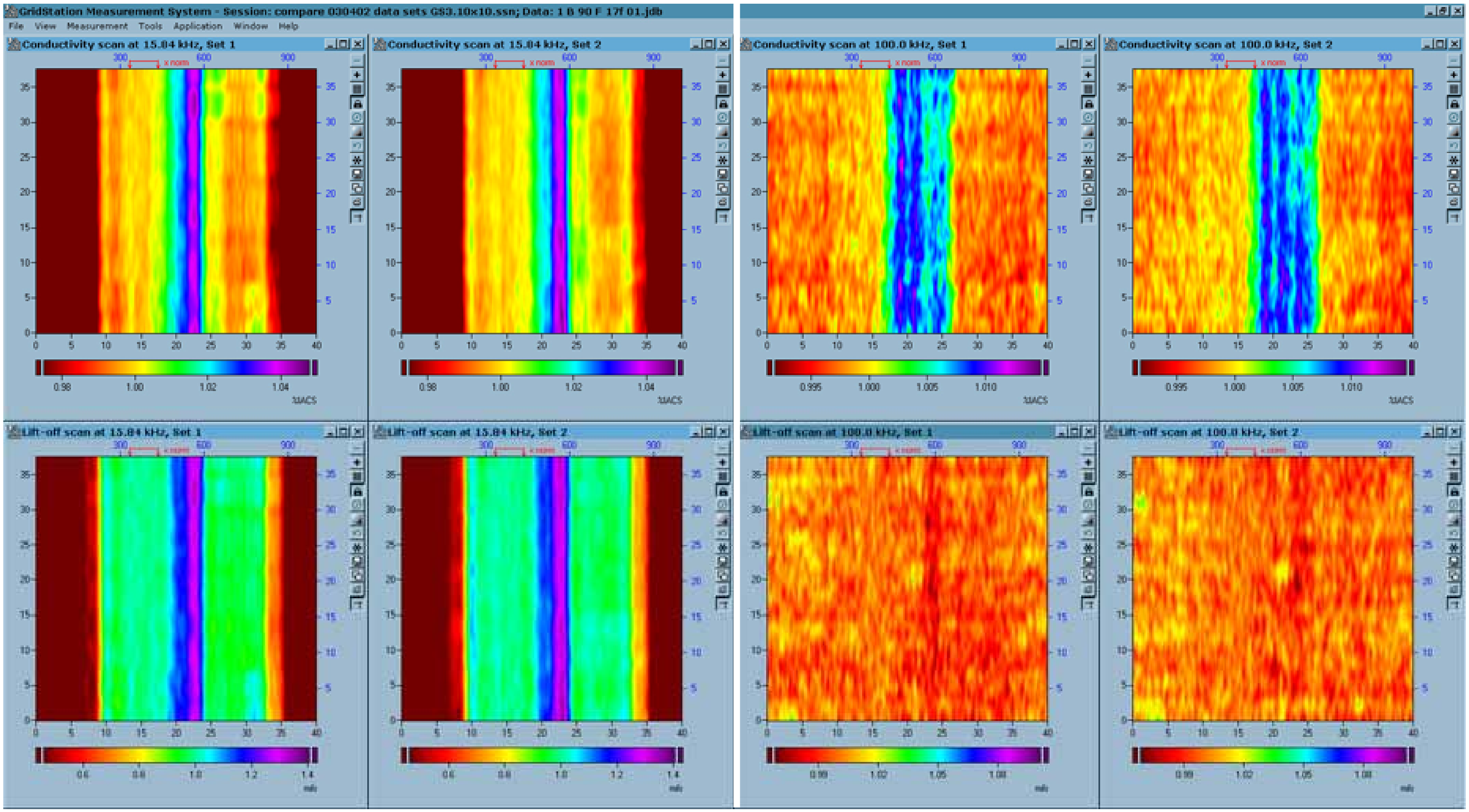
Effective conductivity and lift-off images at 15.84 and 100 kHz for Weld B of Panel #1 produced by clockwise rotation of the pin tool



15.84 kHz **100 kHz**

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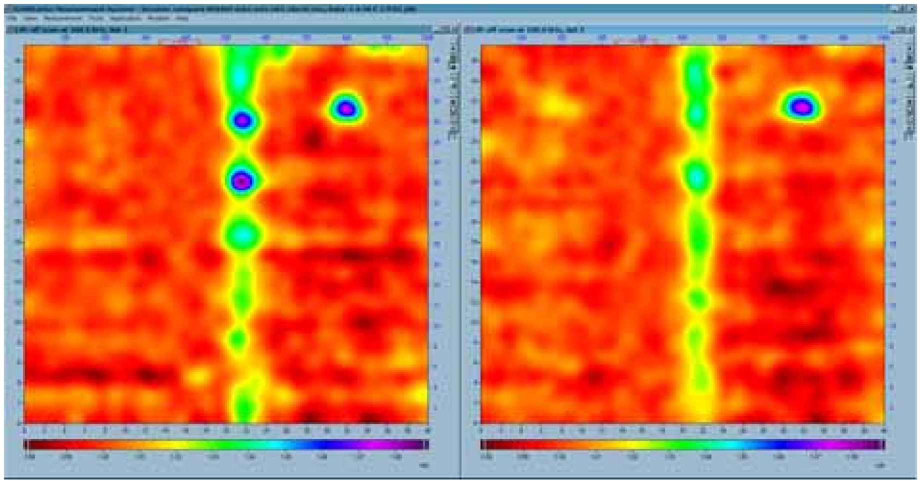
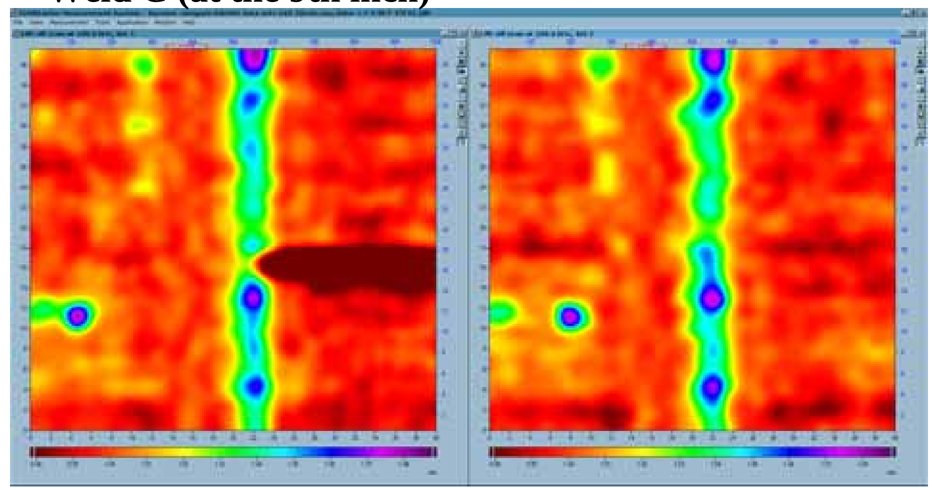
Effective lift-off images for two nominal and one clockwise rotation weld in Panel #1

Weld A



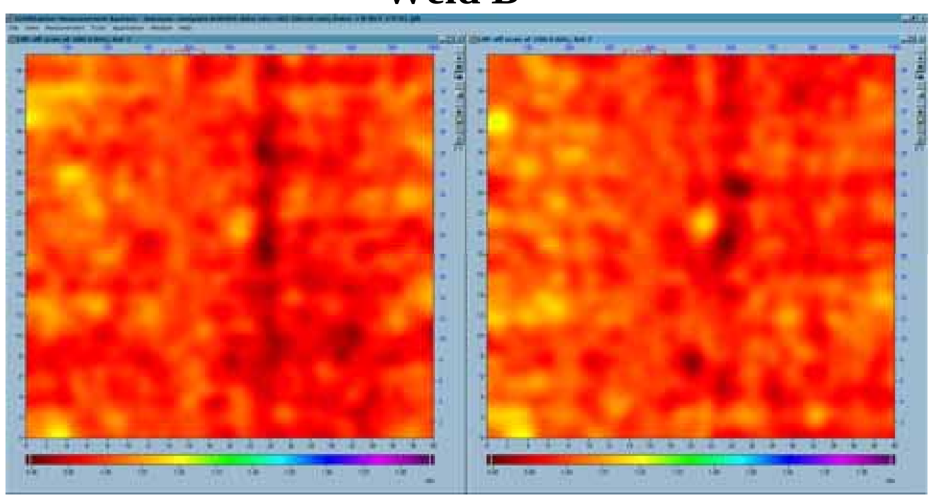
Nominal

Weld C (at the 9th inch)



Nominal

Weld B



Clockwise Rotation

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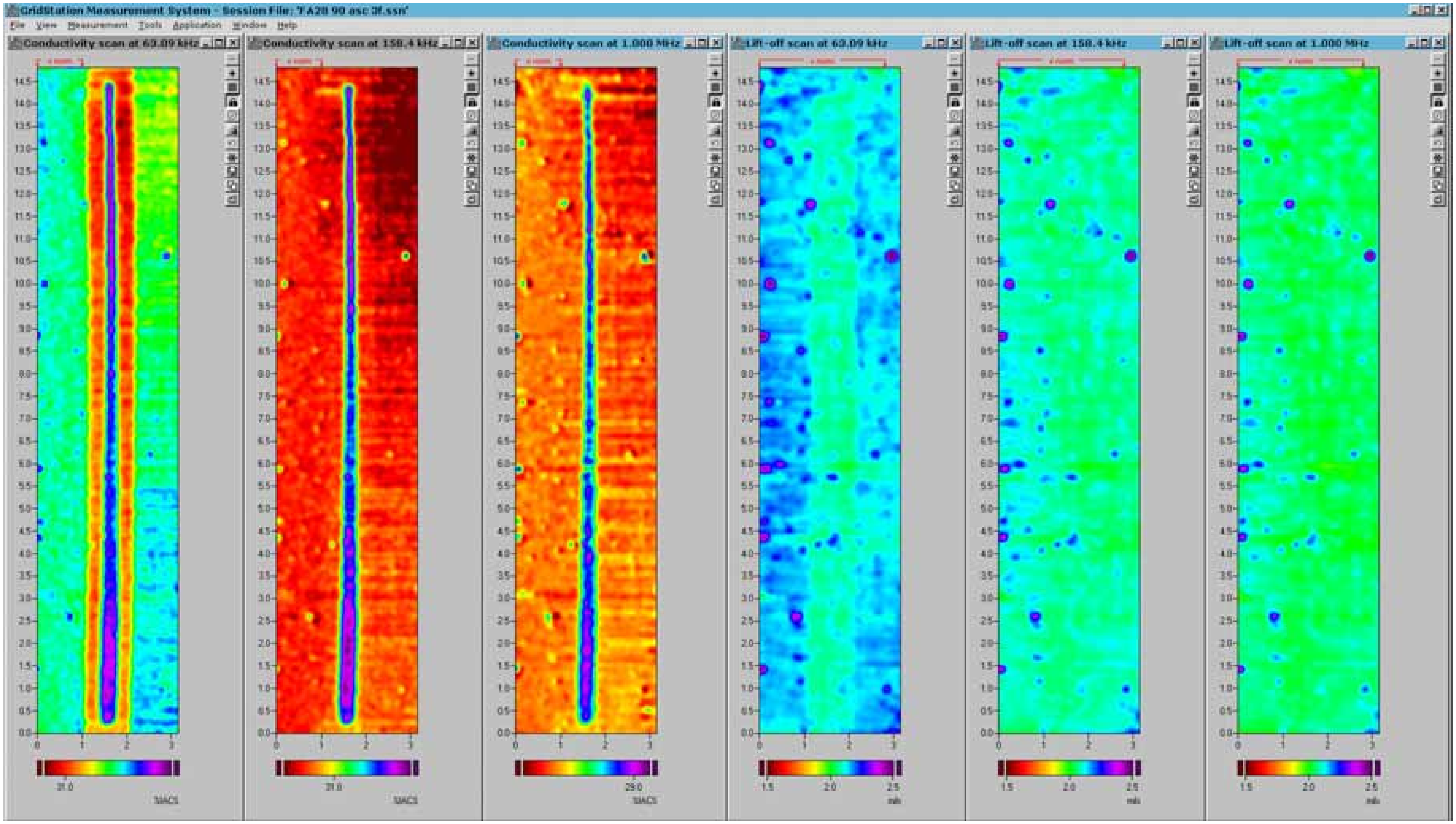
Image constructed from a series of transverse scans of the weld region on Panel 3, Weld C – variable tool speed



63.09 kHz	158.4 kHz	1 MHz	63.09 kHz	158.4 kHz	1 MHz

ECLIPSE AVIATION

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Conclusions – Butt Welds

- MWM electrical conductivity mapping of blind test panels demonstrated high sensitivity to LOP and planar flaws
- MWM conductivity mapping reveals information similar to macroetching
- MWM-Array data obtained in longitudinal scans of the blind test panels confirmed again the previously reported capability to detect and characterize LOP in similar metal FSWs
- This capability is available due to robustness of MWM conductivity measurements that reveal variations associated with metallurgical features within the first 0.020 in. of the LOP zone
- A robust algorithm for determining the presence and size of LOP in dissimilar metal FSWs can also be formulated
- The methods used for characterization of the LOP can be readily automated

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Conclusions – Lap Joints

- An inspection technique was developed that can discriminate between FSWs formed by a qualified welding procedure and FSWs with anomalies due to abnormal welding conditions
- The capability to detect conditions corresponding to nominal and clockwise rotation FSW in lap joints has been demonstrated
- The capability to detect conditions corresponding to variations in tool speed has been demonstrated