Al 2195-T8 plate specimens containing Friction Stir Welds (FSW), provided by Lockheed Martin, were inspected using directional conductivity measurements with the MWM sensor. Sensitivity to lack-of-penetration (LOP) defect size has been demonstrated. The feature used to determine defect size was the normalized longitudinal component of the MWM conductivity measurements. This directional conductivity component was insensitive to the presence of a discrete crack. This permitted correlation of MWM conductivity measurements with the LOP defect size as changes in conductivity were apparently associated with metallurgical features within the first 0.020 in. of the LOP defect zone. Transverse directional conductivity measurements also provided an indication of the presence of discrete cracks. Continued efforts are focused on inspection of a larger set of welded panels and further refinement of LOP characterization tools.
Autogeneous Friction Stir Weld LOP Defect Detection and Sizing Using Directional Conductivity Measurements with MWM™ Eddy-Current Sensor

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Objective

- Demonstrate preliminary capability of the JENTEK MWM™ Sensor with Grid Methods to provide a measure of the lack of penetration (LOP) defect thickness for Friction Stir Welds
Specimens

Four panels with similar FSW geometry representing a range of LOP defect thickness:

- No LOP defect
- 0.02 inch thick LOP defect
- 0.04 inch thick LOP defect
- 0.09 inch thick LOP defect
MWM™ Measurements

- Single Frequency (250 kHz)
- Two-Dimensional images
- One-Dimensional “Line” scans
- Parallel and perpendicular orientation of MWM windings
Meandering Winding Magnetometer

- Thin
- Conformable
- Surface Mountable
- Configurable into an array for imaging

Transfer Impedance = Secondary Voltage / Primary (input) Current
MWM™ Probe and Replaceable MWM™-Array Sensor Tips

Calibration Shunt Tip

Sensor Tip

Single Sensing Element MWM Sensor
Representative Measurement Grids

These grids relate the magnitude and phase of the transimpedance to the liftoff, and
(a) conductivity for aluminum, and
(b) magnetic permeability for low alloy steel

(a) Aluminum

(b) Low-Alloy Steel
MWM™ and MWM-Array Probes

Single Element Conformable MWM Probe for Flat and Curved Surfaces

MWM-Arrays for Continuous On-Line Fatigue Test Monitoring and In-Service Monitoring

MWM-Array for On-Line Contact or Non-Contact C-Scan Imaging
New Portable JENTEK Mini-GridStation™
MWM-Array On-Line

MWM-Array mounted in .25 inch hole

Remote Instrument Module (RIM) with on-line coupon fixture/cables
Future Efforts

➢ Customization of an MWM-Array for scanning of FSW welds with an increased spatial wavelength to provide increased depth of penetration and high spatial image resolution for LOP detect mapping and crack detection

➢ Investigation of multiple frequency methods with a deeper penetration probe for differentiating small LOP defects below 0.03 inches (future effort)

➢ Investigation of high temperature in-process MWM-Array monitoring of microstructure variations
MWM Probe and Scan Orientations Relative to Weld Axis

MWM with Perpendicular Orientation Relative to Weld Axis

1-D Scan Direction

Weld Axis

0.5"
MWM Probe and Scan Orientations Relative to Weld Axis

MWM with Parallel Orientation Relative to Weld Axis

1-D Scan Dir.

0.5”

Weld Axis
MWM Sensor Response
(Minimum Center Region Normalized Conductivity) as a Function of Lack of Penetration Defect Thickness

Minimum Center Region Normalized Conductivity

Locations with
MWM - Detected
Crack
Indications

Normalized Parallel Orientation
MWM Conductivity

Lack of Penetration Defect (Inches)

- 0.02
- 0.04
- 0.06
- 0.08
- 0.1

- 1.09
- 1.08
- 1.07
- 1.06
- 1.05
- 1.04
- 1.03

- LM60-07-B Parallel 1st line No Defect
- LM60-07-B parallel 2nd line No Defect
- LM60-07-DL 3" mark II LOP = 0.02
- LM60-07-DL 6" mark II LOP = 0.02
- LM60-07-DL 9" mark II LOP = 0.03
- LM60-07-DL 12" mark II LOP = 0.04
- LM60-07-DL 15" mark II LOP = 0.04
- LM60-07-DL 21" mark II LOP = 0.04
- LM60-07-N1 3" mark II LOP = 0.09
- LM60-07-N1 6" mark II LOP = 0.09
- LM60-07-A2 15" mark II No Defect
- LM60-07-A2 18" mark II No Defect
- LM60-07-A2 21" mark II No Defect
- LM60-07-E 6" mark II LOP = 0.02
- LM60-07-E 12" mark II LOP = 0.02
- LM60-07-E 18" mark II LOP = 0.02

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Normalized MWM Conductivity Scans for Friction Stir Weld Specimens

Conductivity Scans with MWM Oriented Parallel to Weld

Normalized MWM Conductivity

Transverse Position (inches)

- LM60-07-B, Parallel 1st line, No Defect
- LM60-07-B, parallel 2nd line, No Defect
- LM60-07-D1, 3" mark II, LOP=0.02
- LM60-07-D1, 6" mark II, LOP=0.02
- LM60-07-D1, 9" mark II, LOP=0.02
- LM60-07-D1, 15" mark II, LOP=0.04
- LM60-07-D1, 18" mark II, LOP=0.04
- LM60-07-D1, 21" mark II, LOP=0.04
- LM60-07-N1, 6" mark II, LOP=0.09
- LM60-07-N1, 9" mark II, LOP=0.09
Normalized MWM Conductivity Scans for Friction Stir Weld Specimens

Conductivity Scans with MWM Oriented Perpendicular to Weld

- LM60-07-B, Perpend. 1st Line, No Defect
- LM60-07-B, Perpend. 2nd Line, No Defect
- LM60-07-D1, 3" Mark Perp., LOP = 0.02
- LM60-07-D1, 6" Mark Perp., LOP = 0.02
- LM60-07-D1, 9" Mark Perp., LOP = 0.02
- LM60-07-D1, 15" Mark Perp., LOP = 0.04
- LM60-07-D1, 18" Mark Perp., LOP = 0.04
- LM60-07-D1, 21" Mark Perp., LOP = 0.04
- LM60-07-N1, 3" Mark Perp., LOP = 0.09
- LM60-07-N1, 6" Mark Perp., LOP = 0.09
- LM60-07-N1, 9" Mark Perp., LOP = 0.09

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Normalized MWM Conductivity Scans for Friction Stir Weld Specimens

Conductivity Scans with MWM Oriented Perpendicular to Weld

Only the locations with MWM Crack Indications, Determined by Perpendicular Scan Response Shape (e.g. three adjacent substantially reduced conductivity values, within 0.5% of each other) are shown in this figure.

- ∆ - LM60-07-I2, 21" mark Perp., LOP=0.04
- ● - LM60-07-N1, 3" mark Perp., LOP=0.09
- ☑ - LM60-07-N1, 6" mark Perp., LOP=0.09
- □ - LM60-07-N1, 9" mark Perp., LOP=0.09
Normalized 2-Dimensional MWM Image of Specimen LM60-07-A2, at 250kHz, with MWM Longer Winding Segments Parallel to Weld Axis

LM60-07-A2 Parallel LOP DEPTH = None
Normalized 2-Dimensional MWM Image of Specimen LM60-07-A2, at 250kHz, with MWM Longer Winding Segments Parallel to Weld Axis
Normalized 2-Dimensional MWM Image of Specimen LM60-07-D1, at 250kHz, with MWM Longer Winding Segments Parallel to Weld Axis
Normalized 2-Dimensional MWM Image of Specimen LM60-07-D1, at 250kHz, with MWM Longer Winding Segments Parallel to Weld Axis
Normalized 2-Dimensional MWM Image of Specimen LM60-07-D1, at 250kHz, with MWM Longer Winding Segments Perpendicular to Weld Axis

LM60-07-D1 Perpend. LOP DEPTH = 0.02

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Normalized 2-Dimensional MWM Image of Specimen LM60-07-D1, at 250kHz, with MWM Longer Winding Segments Perpendicular to Weld Axis

LM60-07-D1 Perpend. LOP DEPTH = 0.02

- 1.08-1.09
- 1.07-1.08
- 1.06-1.07
- 1.05-1.06
- 1.04-1.05
- 1.03-1.04
- 1.02-1.03
- 1.01-1.02
- 1-1.01
- 0.99-1
- 0.98-0.99
Normalized 2-Dimensional MWM Image of Specimen LM60-07-I2, at 250kHz, with MWM Longer Winding Segments Parallel to Weld Axis
Normalized 2-Dimensional MWM Image of Specimen LM60-07-I2, at 250kHz, with MWM Longer Winding Segments Parallel to Weld Axis

LM60-07-I2 Parallel LOP DEPTH = 0.04
Normalized 2-Dimensional MWM Image of Specimen LM60-07-I2, at 250kHz, with MWM Longer Winding Segments Perpendicular to Weld Axis
Normalized 2-Dimensional MWM Image of Specimen LM60-07-I2, at 250kHz, with MWM Longer Winding Segments Perpendicular to Weld Axis

LM60-07-I2 Perpend. LOP DEPTH = 0.04
Normalized 2-Dimensional MWM Image of Specimen LM60-07-N1, at 250kHz, with MWM Longer Winding Segments Parallel to Weld Axis
Normalized 2-Dimensional MWM Image of Specimen LM60-07-N1, at 250kHz, with MWM Longer Winding Segments Parallel to Weld Axis

LM60-07-N1 Paralle LOP DEPTH = 0.09
Normalized 2-Dimensional MWM Image of Specimen LM60-07-N1, at 250kHz, with MWM Longer Winding Segments Perpendicular to Weld Axis

LM60-07-N1 Perpend. LOP DEPTH = 0.09
Normalized 2-Dimensional MWM Image of Specimen LM60-07-N1, at 250kHz, with MWM Longer Winding Segments Perpendicular to Weld Axis

LM60-07-N1 Perpend. LOP DEPTH = 0.09
Conclusions

- JENTEK has demonstrated capability to discriminate between LOP defect thickness of 0.02, 0.04 and 0.09 in.

- Sensitivity to LOP defect thickness is due to a correlation with microstructural changes that affect the near surface electrical conductivity within the first 0.01 inches

- JENTEK has demonstrated capability to detect cracks within AFSW