Lack Of Penetration in Friction Stir Welds: Effects on Mechanical Properties and NDE Feasibility

AeroMat 2000 Conference and Exposition
Friction Stir Joining: Session 4

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Acknowledgements and Planned Applications

- **NASA funded Special Development Studies 1998 and 1999**
  - MSFC Materials and Processes ED33
  - MSFC Welding facility in Bldg. 4705
  - MSFC NDE support

- **LMMSS**
  - M&P Test Laboratories
  - NDE Development Support

- **Outside Contractors**
  - JENTEK Sensors, Inc.
  - Sonic Systems International & Automated Inspection Systems
  - RD/Tech
  - Krautkramer

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Overview of Development Activities

- **Vertical FSWelder at MSFC Bldg. 4705**
  - 0.32" & 0.65" Al 2195T8M4 Plate
  - RPM, IPM and plunge force varied during weld development experimental designs
  - Confirmation and full scale panels welded
  - Demonstration hardware completed

- **Square Butt Joint 0.32" & 0.65" Thick**
  - Al2195 and Bi Metal, Al2219 to Al2195-Joints
  - Tapered
  - Two-Sided
  - Joint Gap
  - Repair Methods

- **Mechanical Properties Tests**
  - Tensile, yield and elongation at room, cryogenic and elevated temperatures
  - SCT and SST at room, cryogenic and elevated temperatures
FSWeld Mechanical Properties Specimens & Tests

- Room Temperature Tensile Specimen

- Cryogenic & Elevated Temperature Tensile Specimen

- Test Temperatures
  - -423°F
  - -320°F
  - 70°F
  - +200°F
  - +300°F
FSWeld Mechanical Properties Test Results

0.320” & 0.650” RT & Cryogenic Tests
- DOE, verification and full-length
- Reduction in strength vs thickness
- Elongation consistent and reproducible

0.320” & 0.650” Cryogenic Enhancement in Strength
- 1.5X Ftu and Fty
- Elongation consistent with RT
- Elevated temp, Reduction
- 0.75X Ftu and Fty @ +300F
FSWeld Lack Of Penetration

- **LOP - Lack Of Penetration**
  - Root Side of Weldment
  - Surface Breaking Defect
  - Results from incomplete penetration of the DXZ
  - Frequently referred to as "kissing bond"
  - Requires micro examination to detect
  - Range of LOP studied from 0.02 to 0.075"

AeroMat 2000LOP MechProp.ppt
Rev Date: 04/12/2000

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LOP in FSWeld: Mechanical Properties Results

- **LOP - RT and Cryo Tensile Results**
  - Consistent, repeatable results
  - Predictable as a function of LOP depth
  - UTS results compared closely to gross fracture stress at ultimate failure after simulated service tests
FSWeld Surface Crack Tension Tests

- Tests conducted at RT, -320F and -423F
- Flaws oriented parallel to the weld direction and perpendicular to the load direction
- Initiated by EDM and increased to size under cyclic axial tension
- CL Crown and CL Root locations demonstrated lowest toughness
- Li and Ti Root locations generated wide scatter in toughness data

<table>
<thead>
<tr>
<th>a/2c Ratio</th>
<th>a (in)</th>
<th>2c (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.50</td>
<td>0.125</td>
<td>0.250</td>
</tr>
<tr>
<td>0.20</td>
<td>0.150</td>
<td>0.750</td>
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FSWeld SCT Gross Fracture Stress Results

- CL flaw data plotted
- Limited data
- Threshold of 0.180” suggested (a/2c = 0.5 and a/2c = 0.2)
- SST data included

SCT at -320F with LI Root Flaw

SCT at -320F with CL Crown Flaw
FSWeld Simulated Service Tests

Fracture Specimen
(Use NC Tape F-4)

Simulated Service Test Conditions
- Pre-cracked flaws and natural LOP
- Multiple flaw locations
- RT, -423°F & +300°F
- Multiple RT proof cycles, hold at specified stress, repeated for multiple mission simulation

Note
Sawcut dimensions to be 4.0" x 12.0"
FSWeld Simulated Service Tests Results

- **LOP - SST Results**
  - Consistent, repeatable results
  - Predictable as a function of LOP depth
  - Superior to fusion weld results
FSWeld Simulated Service Tests Results

0.25 X 0.80" Flaw

0.06" LOP

Friction Stir Weld SCT & SST Data
0.320" 2195P/2195P

Gross Fracture Stress (psi)

Crack Length 2c (inches)

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FSWeld NDE Feasibility for LOP Inspection

- Conventional Eddy Current
  - Zetec

- High Sensitivity Eddy Current
  - MWM sensor
  - Jentek Sensors

- Conventional Ultrasonics
  - Contact & Immersion
  - 0, 45 and 60° Transducers
  - Shear wave
  - Creeping wave
  - Dual Element
  - Sonic Systems/Automated Inspection Systems
  - Krautkramer

- Phased Array UT
  - 64 element array
  - Shear wave
  - R/D Tech
FSWeld NDE Feasibility Results

- **MWM Eddy Current**
  - Jentek Sensors, Inc.
  - 0.040” detected
  - Possibility of greater detectability

**Figure 3:** Normalized MWM Conductivity Scans for Friction Stir Weld Specimens, with MWM Oriented Perpendicular to Weld.
FSWeld NDE Feasibility Results

- **Phased Array UT**
  - R/D Tech Inc.
  - 0.060" LOP results shown
  - Possibility of greater detectability
FSWeld NDE Feasibility Results

- **Phased Array UT**
  - LMSS Michoud Operations
  - 0.030” and 0.060” LOP detected post proof
Results

- **Conventional Ultrasonics**

- **Sonic Systems/Automated Inspection Systems**
  - Creeping wave and Dual Element FAST probes detected 0.040" LOP intermittently
  - Easily detected deep LOP (0.090"

- **Krautkramer**
  - Contact & Immersion 0, 45 and 60° Transducers, and Shear wave
  - Readily detected 0.060" deep LOP

- **Conventional Eddy current**

- **Zetec**
  - Readily detected 0.090" LOP, but not 0.040".
  - Recommended development of other NDE methods
Results

- Mechanical property tests of FSW in 0.320" Al 2195 demonstrated an average RT UTS of 59 ksi, with a cryogenic enhancement factor of 1.5 and elongation of ~10%. All of these values are above those currently attainable with fusion weld processes. 0.650" Al 2195/Al 2219 FSWelds average RT UTS is 47 ksi with similar cryo enhancement and elongation.

- Lack Of Penetration is NOT an inherent condition in FSWelds of Al 2XXX alloys. Adequate process controls preclude LOP.

- SCT and SST tests of induced cracks resulted in gross fracture stress values above the values associated with current fusion weld processes.

- Tensile and fracture test results of LOP indications demonstrate predictable results well above comparable fusion welds at RT, cryogenic and elevated temperatures.

- Multiple NDE techniques exist or have shown feasibility to detect LOP in FSWelds.