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Dayton, Ohio

Self-Reacting Friction Stir Weld for Aluminum
Complex Curvature Applications

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Acknowledgements

NASA Led Space Launch Initiative / Next Generation Launch Technologies (SLI/NGLT) Friction Stir Welding Complex Curvature Risk Reduction Program

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- Chip Jones - Program Manager, NASA MSFC
- Bruce Braiford - Director, NCAM University of New Orleans
- Jules Schneider - Program Manager, Lockheed Martin
# Conventional vs. Self-Reacting

<table>
<thead>
<tr>
<th>Conventional (FPT and APT) FSW</th>
<th>Self-Reacting (SR-FSW)</th>
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</thead>
<tbody>
<tr>
<td>- The FSW tool consists of a crown-side shoulder and a pin</td>
<td>- The FSW tool consists of two shoulders with a pin that goes through the base material, the bottom shoulder is attached to the pin</td>
</tr>
<tr>
<td>- The forge load is provided by controlling the position and/or load of the shoulder</td>
<td>- The forge load is provided by controlling the relative position and/or load between the two shoulders</td>
</tr>
<tr>
<td>- Requires a backing anvil with support structure to react the forge load</td>
<td>- Eliminates the backing anvil requirement</td>
</tr>
</tbody>
</table>
Cryogenic Tankage Welding Needs

Large Fuel Tanks are comprised of four major weld configurations

- **Longitudinal**
  - In production on ET and Delta II and IV barrels

- **Circumferential**
  - Demonstrated up to 14 ft. dia. since 1998
  - 27.5 ft. dia demonstration planned in late 2003

- **Complex Contour**
  - Gore-to-gore for large domes currently in work
  - Conformal configurations for future launch vehicles

- **Circular**
  - In research and development
NGLT Complex Curvature SR-FSW Risk Reduction Program

2002

- ATP 5
- Program PDR
- UWS CDR 15
- ET FSW Barrel Welds in Production

2003

- 2195 ATR 5
- Program CDR
- Intermediate Scale Demo 1
- Full Scale Demo 30
- Program Completion 30

Weld Process Development
- Establish Weld Schedule & Set-up parameters

Full Scale Weld Demo
- Complex Curvature SR-FSW on UWS / Simple Fixture, Tapered Weld Lands

Intermediate Scale Weld Demo
- Complex Curvature SR-FSW on Fixed Track Tool, Constant Thickness Weld Lands

Universal Weld System
- 6 Axis, large envelope, SR-FSW system
Building Block Design-to-Manufacture Approach

Weld Process Development
- MTS Adjustable, Adaptable Pin Tool (AdAPT) Weld Head, Controller and Product Development Fixture (PDF)
- Constant Thickness Al2219-T87 to Al2219-T87 Flat Panels
  - 0.320, 0.360 and 0.385 gage

Weld Process Transfer
- MTS AdAPT Weld Head & Controller on Gore to Gore Weld Tool
- 0.320 gage Al2219-T87 Curved Confidence Panels (24” & 84”)

Intermediate Hardware Demonstration
- MTS AdAPT Weld Head & Controller on Gore to Gore Weld Tool
- 0.320 gage Al2219-T87 Quarter Panel Fabrication
Weld Process Development

Approach
- Utilize a Designed Experiment approach to develop an operating box for welding Al2219
  - 0.320, 0.360 and 0.385 gage
  - Load, travel and rotation speed
  - Visual and radiographic inspection
  - Microstructural analysis
  - Tensile testing at ambient & LN2 temperatures

Success Criteria
- Average room temperature $F_{tu} \sim 48$ ksi
- LN2 enhancement of 1.2
- Visual & Radiographic Inspection
# Weld Process Development

Mechanical property goals for 0.320 and 0.400 gage were accomplished over a range of rotation and travel speeds and forging load.

**RT UTS**
- Goal: Average of 48 ksi
- Actual: Average of 51.6 ksi

**LN2 (-320°F) UTS**
- Average 57.6 ksi (1.2 enhancement)
- Average of 62.0 ksi

<table>
<thead>
<tr>
<th>Weld Schedule</th>
<th>Thick. (in.)</th>
<th>Ultimate Strength (ksi)</th>
<th>Yield Strength (ksi)</th>
<th>2 inch Elong. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>RT Ave</td>
<td>LN2 Ave</td>
<td>Ratio</td>
</tr>
<tr>
<td>Min</td>
<td>0.320</td>
<td>52.5</td>
<td>64.7</td>
<td>1.23</td>
</tr>
<tr>
<td>Min</td>
<td>0.400</td>
<td>52.2</td>
<td>60.0</td>
<td>1.15</td>
</tr>
<tr>
<td>Nom</td>
<td>0.320</td>
<td>52.6</td>
<td>63.9</td>
<td>1.21</td>
</tr>
<tr>
<td>Nom</td>
<td>0.400</td>
<td>52.9</td>
<td>64.7</td>
<td>1.22</td>
</tr>
<tr>
<td>Max</td>
<td>0.320</td>
<td>48.8</td>
<td>60.5</td>
<td>1.24</td>
</tr>
<tr>
<td>Max</td>
<td>0.400</td>
<td>50.8</td>
<td>58.5</td>
<td>1.15</td>
</tr>
</tbody>
</table>
Weld Process Development

Al2219 to Al2219 Set-up Verification DOE

FTU (KSI)

-320 Goal

RT Goal

Weld Condition

Min heat / No offset / 0.320”
Min heat / No offset / 0.400”
Max heat / No offset / 0.320”
Max heat / Max offsets / 0.320”
Min heat / Max offsets / 0.320”
Max heat input / Max offsets / 0.320”
Max heat input / Max offsets / 0.400”
Weld Process Development

Al2219 to Al2219 Set-up Verification DOE

![Bar chart showing FTU (KSI) vs. Weld Condition]
**Weld Process Development**

**Al2219 to Al2219 Tack / Weld Schedule Verification**

- Tack and self reacted welds without side restraints were conducted to evaluate the effects from the tack on the schedule.
  - 2 Weld Panels At Nominal Schedule
  - 1 Weld panel at Maximum Schedule
  - 1 Weld Panel A Minimum Schedule

![Graph showing FTU (KSI) for different weld conditions]

**All Panels Exceeded Room and -320 °F Strength Goals**
Weld Process Development

Effects of Oil Contamination

Oil contamination testing showed no significant decrease in mechanical properties.
Weld Process Transfer

Approach

- Modify an existing fusion weld 22 ft. dia. dome weld tool to accommodate the AdAPT weld head, induced loads from the FSW process and clamping requirements

- Ensure weld schedule transfer from test fixture to dome tooling using short and full length confidence panels. Considerations include:
  - Dynamic weld head attitude
  - Tacking procedure
  - Allowable fit-up tolerances
  - Start/stop tab procedure
Weld Process Transfer

Perform weld process verification, using “Best” set of parameters as determined from Weld Process Development and geometrical variance

- Curved 24” panels at bottom, middle, and top positions in Gore-to-Gore tool
- Curved 24” panels at bottom and top positions to validate start / stop tab procedures
- Full length constant curvature confidence panels

Success Criteria
- Average room temperature Ftu ~ 48 ksi
- LN2 enhancement of 1.2
- Visual & Radiographic Inspection
Intermediate Hardware Fabrication

Tooling Modification

- Tool Requirements
  - Track and drive system to hold, position and drive AdAPT Weld Head
  - Signal interface to MTS Control System
  - Maintain Pin Tool angle normal (+/- 0.25” deg) to part surface
  - Removable anvil (used for fixed pin tack welding)
  - Provide access for pin removal and backside shoulder at all travel positions
  - Part clamping at 100 pounds per linear inch (minimum)
    - 24” Test Panels
    - 84” Confidence Panels
    - Intermediate scale Gore Panels
  - Support for hydraulic manifold and hoses
  - Provide camera for video recording of leading and trailing of weld
Intermediate Hardware Fabrication

Intermediate Scale Weld Tool Modification - Design

Gore Panels
Intermediate Hardware Fabrication

Intermediate Scale Weld Tool Modification - Installation

Weld Track & Carriage

Electronic Enclosures & Disconnect
Weld Process Transfer

Weld schedule transfer from the PDF to the Gore-to-Gore tool was successful:

- Fixture was not specially designed to hold short panel - panels required a tack weld
- Average cold, nominal and hot mechanical meet project goals

![Bar chart showing FTU (KSI) values for different weld locations and temperatures.](chart.png)
Weld Process Transfer

RT mechanical properties for the 24” panels

- Hot - Bottom panel premature abort due to erroneous control limit

- Nom Bottom: Ave = 51.6, SD = 0.78
- Nom Top: Ave = 48.2, SD = 1.75
- Hot Bottom: Ave = 50.0, SD = 1.95

UTS (ksi)

Panel Location (inches)

Nom Bottom —— Nom Top —— Hot Bottom —— RT Target = 48 ksi
Weld Process Transfer

LN2 mechanical properties for the 24" panel with weld tabs

- Hot - Bottom panel premature abort due to erroneous control limit

![Graph showing UTS (ksi) vs. Panel Location (inches)]

- Nom Bottom: NK21
  - Ave = 62.2
  - SD = 3.38

- Nom Top: NK22
  - Ave = 59.9
  - SD = 1.76

- Hot Bottom: NK23
  - Ave = 62.9
  - SD = 2.20

RT Target = 57.6 ksi
Intermediate Hardware Fabrication

84” full length confidence panels were successfully welded prior to welding the demonstration article

• Confidence panels were welded to validate full length welding ability with addition of start / stop tabs
Weld Process Transfer

RT mechanical properties for the 84” panels
- Weld schedule transfer from the 24” to 84” panels was successful
- Hot panel did not meet goal due to poor seam alignment
Weld Process Transfer

RT mechanical properties for the 84” panels
- Weld schedule transfer from the 24” to 84” panels was successful
- Hot panel did not meet goal due to poor seam alignment
**Intermediate Hardware Demonstration**

**Confidence Panel Results**

- **Development Macro**
- **Confidence Macro: End of Weld**
- **Confidence Macro: Mid-Weld**
- **Confidence Macro: Weld Start**
- **Typ. Crown Appearance**
- **Typ. Tensile Fracture**

**0.320” Thick Al2219/Al2219 Welding (ksi):**

<table>
<thead>
<tr>
<th></th>
<th>Fusion Ave Req</th>
<th>FSW Goal</th>
<th>FSW Ave</th>
<th>FSW Std Dev</th>
</tr>
</thead>
<tbody>
<tr>
<td>Room Temp</td>
<td>40</td>
<td>48</td>
<td>51.2</td>
<td>0.53</td>
</tr>
<tr>
<td>-320°F</td>
<td>48</td>
<td>58</td>
<td>63.1</td>
<td>0.72</td>
</tr>
</tbody>
</table>

- Seamless flat to complex curvature weld schedule transition
- Exceptionally consistent, high tensile results
Intermediate Hardware Fabrication

Manufacturing Flow

- Trim Gore Panels
- Tool Fit Check and Functional Checkout
- Obtain and Inspect Gore Panels (3)
- Prep Gore Panel Weld Land Edges
- Install Gore Panels (2) on Weld Fixture
- Friction Stir Weld Joint 1
- Friction Stir Weld Joint 2
- Install Gore Panel #3
- Weld Short & Full Length Confidence Phils
- Tack Weld and SR
- Inspect (NDI) Welds
- Ship to MSFC
- Visual
- X-Ray

-T80W0501
-T80W0503
Intermediate Hardware Fabrication

Intermediate Scale Gore Configuration

- Weld land thickness
  - 0.320" constant

Section A-A
Intermediate Hardware Fabrication

Set up and welding of the intermediate gore-to-gore welds

- Partial penetration fixed pin, continuous length tack weld
  - Completely consumed by the self-reacting weld
- Start and stop tabs for the weld initiation and tail-out, respectively

Gore panels during welding

Start tab after Tack weld

Start tab after SR-FSW

Run-out tab after SR-FSW
Intermediate Hardware Fabrication

Success demonstration of an Al2219 self-reacting gore to gore weld
  • 84 inch long - 0.320 inch constant thickness weld lands
  • Slight chem-milled weld lands resulted in localized “flash”
The Next Step

The Universal Weld System (UWS) will be operational at the Michoud Assembly Facility in Sept. 2003

- Designed and fabricated by MTS Systems
- Enables fabrication of a External Tank size (27.5 ft dia.) domes and barrels
- Quarter Panel fabrication with a flexible tooling approach will be performed by 10/1/03
Summary

Lockheed Martin and the NASA have advanced the self-reacting friction stir weld technology for complex curvature aluminum alloys.

- Successful weld process development for 0.320” Al 2219
- Weld quality exceeds strength goals

The Universal Weld System enables development and implementation of large scale complex geometry hardware fabrication.

- Al2195 tapered thickness gore-to-gore demonstration program planned for September 2003