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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 Brailsford - 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>
</tr>
</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

- J: ATP 5
- J: Program PDR
- S: UWS CDR
- O: ET FSW Barrel Welds in Production
- N: 2195
- D: Program CDR

2003

- J: Intermediate Scale Demo
- F: Full Scale Demo
- M: 30
- A: Program Completion

Full Scale Weld Demo
- Complex Curvature SR-FSW on UWS / Simple Fixture, Tapered Weld Lands
- Complex Curvature SR-FSW on Fixed Track Tool, Constant Thickness Weld Lands

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

Intermediate Scale Weld Demo

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 Ftu ~ 48 ksi
- LN2 enhancement of 1.2
- Visual & Radiographic Inspection
<table>
<thead>
<tr>
<th>Weld Schedule</th>
<th>RT</th>
<th>UTS</th>
<th>LN2 (320°F) UTS</th>
<th>Goal: Average of 48 ksi</th>
<th>Actual: Average of 51.6 ksi</th>
<th>2 inch Elong. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weld Thickness (in.)</td>
<td>RT</td>
<td>Ave</td>
<td>Ave</td>
<td>Ratio</td>
<td>RT</td>
<td>Ave</td>
</tr>
<tr>
<td>Min</td>
<td>0.320</td>
<td>52.5</td>
<td>25.5</td>
<td>1.17</td>
<td>15.5</td>
<td>11.6</td>
</tr>
<tr>
<td>Nom</td>
<td>0.400</td>
<td>52.6</td>
<td>25.1</td>
<td>1.11</td>
<td>12.9</td>
<td>12.9</td>
</tr>
<tr>
<td>Max</td>
<td>0.320</td>
<td>48.8</td>
<td>26.2</td>
<td>1.15</td>
<td>28.0</td>
<td>24.3</td>
</tr>
<tr>
<td>Max</td>
<td>0.400</td>
<td>50.8</td>
<td>27.0</td>
<td>1.20</td>
<td>27.0</td>
<td>24.4</td>
</tr>
</tbody>
</table>

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.
Weld Process Development

Al2219 to Al2219 Set-up Verification DOE

FTU (KSI)

-320 Goal

RT Goal

Weld Condition
Weld Process Development

Al2219 to Al2219 Set-up Verification DOE

FTU (KSI)

Max heat input / Mod Max offsets / Max Mismatch / 0.320"  Min heat / Mod Max offsets / 0.400"  Max heat input / Mod Max offsets / 0.400"

-320 Goal  RT Goal

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

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]

**FTU (KSI)**

**Weld Location**
Weld Process Transfer

RT mechanical properties for the 24” panels

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

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

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

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
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
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

![Graph showing Ultimate Tensile Strength (ksi) vs. Panel types: Nominal, Cold, Hot, Nom-Cold Split, Nom-Hot Split. Sleep lines indicate average UTS, and bars represent standard deviation. -320F Goal = 57.6 ksi]
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

7xMs, 24xRTs, 18x–320s Per Conf. Panel
Intermediate Hardware Fabrication

Manufacturing Flow

Obtain and Inspect Gore Panels (3) → Tool Fit Check and Functional Checkout → Trim Gore Panels
- T80W0501
- T80W0503

Install Gore Panels (2) on Weld Fixture
- T80W0501

Prep Gore Panel Weld Land Edges

Weld Short & Full Length Confidence Pnls
- T80W0501

Friction Stir Weld Joint 1

Install Gore Panel #3

Friction Stir Weld Joint 2

Ship to MSFC

Inspect (NDE) Welds
- Visual
- X-Ray
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
- Successful transfer from the “lab” scale to the production scale tool
- 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