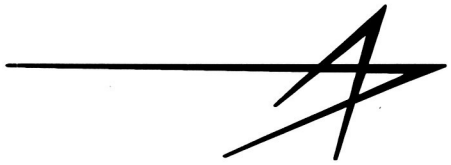


# Aeromat 2003 - Dayton, Ohio

# *2XXX Aluminum Self Reacting Friction Stir Weld Development*

**Randy J. Brown, Jules Schneider, Paula J. Hartley**

***Lockheed Martin Space Systems Company - Michoud Operations***

**Carolyn Russell, Kirby Lawless, Chip Jones**

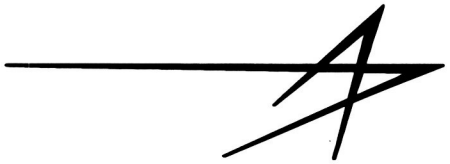
***NASA Marshall Space Flight Center***

# Acknowledgements

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

- **Funded through the University of New Orleans National Center for Advance Manufacturing University Research Cooperative Agreement**
  - **Chip Jones - Program Manager, NASA MSFC**
  - **Bruce Brailsford - Director, NCAM University of New Orleans**
  - **Jules Schneider - Program Manager, Lockheed Martin**

# Weld Process Development



- **Weld Process Development (1.2)**
  - LM AdAPT Weld Head and Controller
  - Constant Thickness Al2219 to Al2219 and Al-Li to Al-Li Flat Panels

- **Intermediate Hardware Demonstration (1.3.1)**
  - LM AdAPT Weld Head and Controller
  - Constant Thk Al2219 Curved Test Panels (24" and 84")
  - Al2219 Gore to Gore Weld Demo
  - Tapered Thk Al-Li Curved Test Panels (24" and 84")

- **Full Scale Hardware Demonstration (1.3.2)**
  - UWS AdAPT Weld Head and Controller
  - Tapered Thickness Al-Li Curved Test Panels (24' and 144" length)
  - Al-Li Gore to Gore Weld Demo

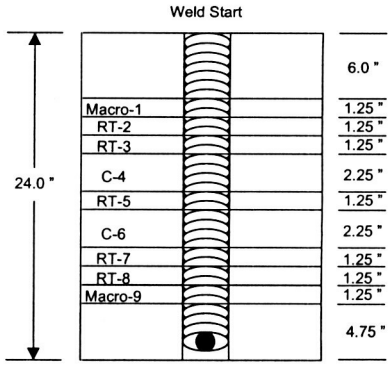
# Weld Process Development

## Approach

- Execute a two-phased Design of Experimental (DOE) approach
  - *Process DOE* to establish rotation and travel speeds and forge load
  - *Set-up DOE* to establish allowable gap and centerline offset

- Determine the effects of process parameters on strength and weld quality
  - –Room and -320 degrees F tensile testing
  - –Metallurgical and NDE evaluation

- Weld quality goals
  - – Visual and Radiographic acceptable
  - – Room temperature ultimate strength
    Minimum Average of 48.0 KS
  - –- 320 degrees F ultimate strength
    Minimum Average of 57.6 KSI




RT: Room temperature tensile
C: -320 degree F tensile

# Weld Process Development

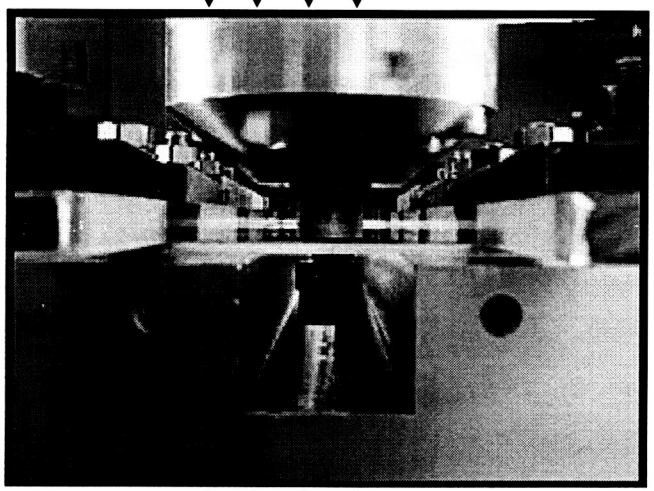
## *Self Reacting Friction Stir Weld (FSW) Process*

**Uncontrollable Variables**

Thickness Variation
Panel Temperature
Pin Tool Wear
Surface Oxide

**Inputs**

Rotation Speed →
Travel Speed →
Forge Load →
Thickness →



**Outputs**

← Visual Weld Quality
← NDE Weld Quality

Pin Design
Material Alloy
Joint Configuration
Holding Fixture Heat Sink

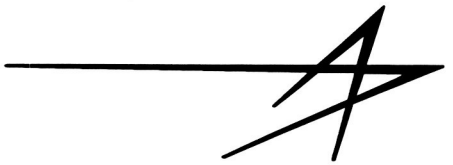
**Fixed Inputs**

# Weld Process Development

## *Design of Experiment*

- **A Designed Experiment is a Series of Tests in Which Predetermined Systematic Changes are Made to be the Input Variable so that Output Responses can be Statistically Analyzed**
  - Determines which variables are significant to the response and influential on the response
  - Determine the input variables and settings to achieve desired goal of the response (Response Surface)
  - Determine where to set the influential variables so that the variability of the response is small (Robust Design)
  - Determine where to set the influential variables so that the effects of the uncontrollable variables are minimized (Robust Design)

# Weld Process Development



## *Design of Experiment Process Steps*

- Determine the Goals
- Define the Measures of Success
- Verify Feasibility (Bounding Panels)
- Design the Experiment (DOE Panels)
- Run the Experiment
- Collect and Analyze the Data
- Determine and Verify the Optimum (Verification Panel)
- Act on the Results

# Weld Process Development

## *Al2219 to Al2219 Parameter Design of Experiment (DOE)*

### Bounding Panels

| Trial | Rotation (RPM) | Travel (IPM) | Load (Lbs.) | Thickness (Inches) |
|---|---|---|---|---|
| 1 | Low | Low | High | 0.32 |
| 2 | Mean | Low | High | 0.32 |
| 3 – Hot Weld | High | Low | High | 0.32 |
| 4 | Low | High | High | 0.32 |
| 5 | Mean | High | High | 0.32 |
| 6 | High | High | High | 0.32 |
| 7 | Low | Low | Low | 0.32 |
| 8 | Mean | Low | Low | 0.32 |
| 9 | High | Low | Low | 0.32 |
| 10 – Cold Weld | Low | High | Low | 0.32 |
| 11 | Mean | High | Low | 0.32 |
| 12 | High | High | Low | 0.32 |
| 13 | Low | Low | High | 0.40 |
| 14 | Mean | Low | High | 0.40 |
| 15 – Hot Weld | High | Low | High | 0.40 |
| 16 | Low | High | High | 0.40 |
| 17 | Mean | High | High | 0.40 |
| 18 | High | High | High | 0.40 |
| 19 | Low | Low | Low | 0.40 |
| 20 | Mean | Low | Low | 0.40 |
| 21 | High | Low | Low | 0.40 |
| 22 – Cold Weld | Low | High | Low | 0.40 |
| 23 | Mean | High | Low | 0.40 |
| 24 | High | High | Low | 0.40 |

### DOE Panels

| Run Number | Trial | Rotation (RPM) | Travel (IPM) | Load (Lbs.) | Thickness (Inches) |
|---|---|---|---|---|---|
| 1 | 3 | High | Low | High | 0.32 |
| 2 | 13 | Mean | Mean | High | 0.40 |
| 3 | 7 | High | Low | High | 0.40 |
| 4 | 11 | Low | High | Low | 0.36 |
| 5 | 20 | Low | Mean | Low | 0.40 |
| 6 | 15 | Mean | High | Mean | 0.40 |
| 7 | 18 | High | Low | Mean | 0.32 |
| 8 | 2 | High | High | Low | 0.32 |
| 9 | 5 | Low | Low | Low | 0.40 |
| 10 | 2 | High | High | Low | 0.32 |
| 11 | 14 | High | Mean | Mean | 0.40 |
| 12 | 4 | Low | High | High | 0.32 |
| 13 | 10 | High | Low | Low | 0.36 |
| 14 | 6 | High | High | Low | 0.40 |
| 15 | 9 | High | High | High | 0.36 |
| 16 | 12 | Low | Low | High | 0.36 |
| 17 | 19 | Low | High | High | 0.32 |
| 18 | 1 | Low | Low | Low | 0.32 |
| 19 | 16 | Mean | Low | Low | 0.40 |
| 20 | 3 | High | Low | High | 0.32 |
| 21 | 1 | Low | Low | Low | 0.32 |
| 22 | 8 | Low | High | High | 0.40 |
| 23 | 17 | Mean | High | Low | 0.32 |

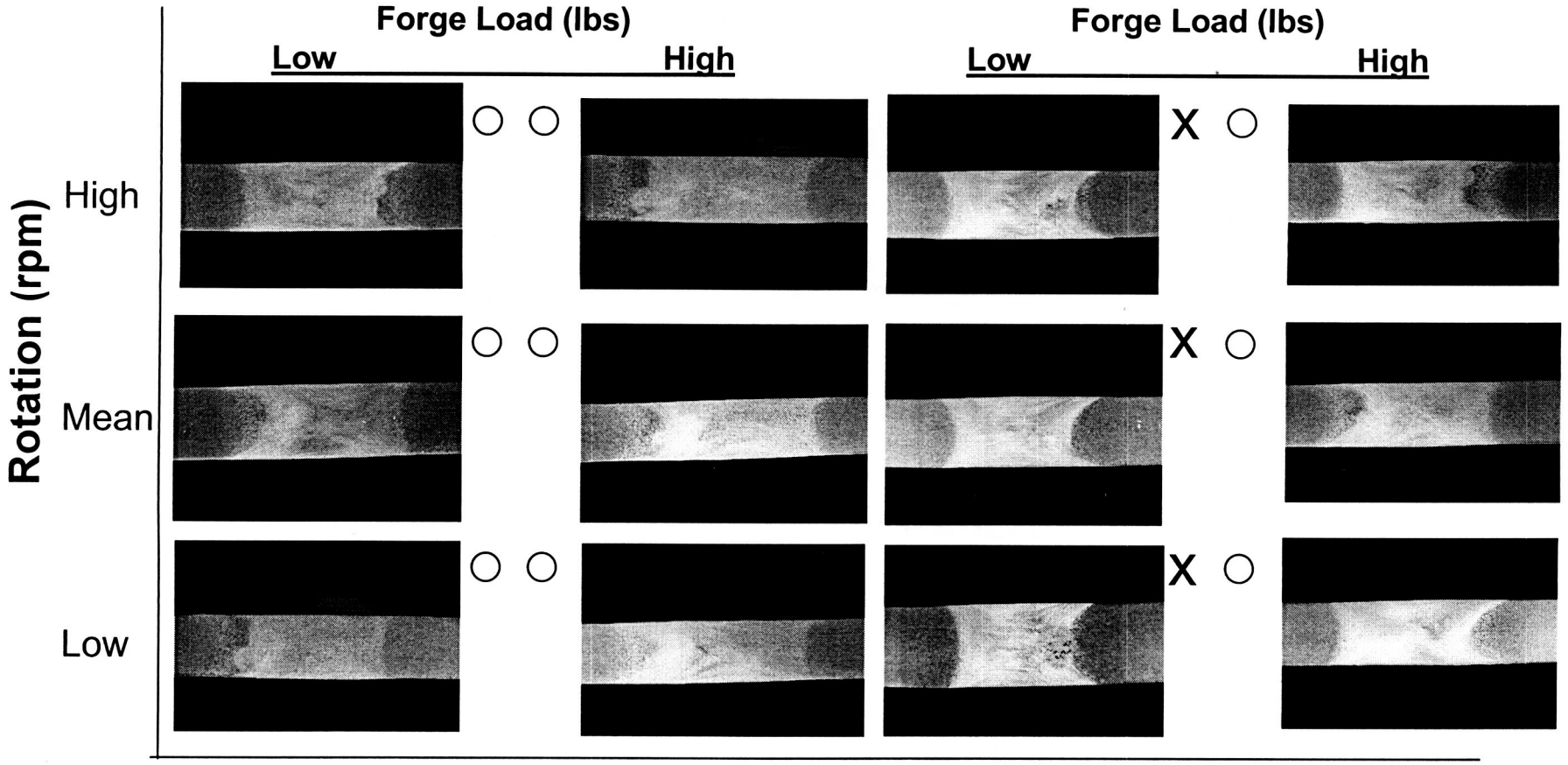
### Verification Panels

| Trial | Rotation (RPM) | Travel (IPM) | Load (Lbs.) | Thickness (Inches) |
|---|---|---|---|---|
| 1 – Minimum Heat 0.32" | Minimum | Maximum | Minimum | 0.32 |
| 2 – Minimum Heat 0.40" | Minimum | Maximum | Minimum | 0.40 |
| 3 – Nominal Heat 0.32" | Nominal | Nominal | Nominal | 0.32 |
| 4 – Nominal Heat 0.40" | Nominal | Nominal | Nominal | 0.40 |
| 5 – Maximum Heat 0.32" | Maximum | Minimum | Maximum | 0.32 |
| 6 – Maximum Heat 0.40" | Maximum | Minimum | Maximum | 0.40 |

# Weld Process Development

## *Al2219 to Al2219 Bounding Parameter DOE Results*

### Microstructural and Tensile Results for 0.320 gage



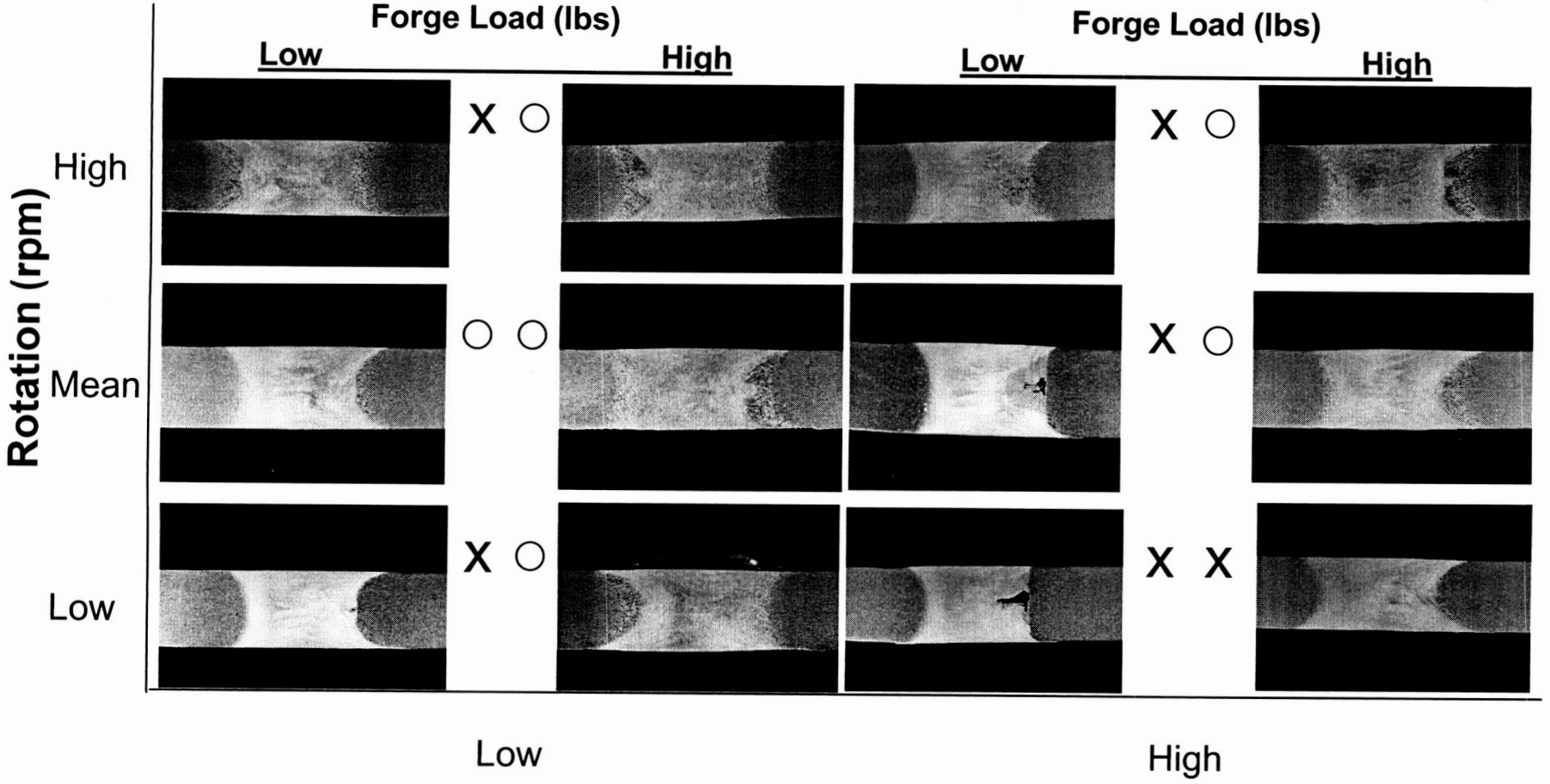

○ X-Ray Acceptable

X X-Ray Rejectable

# Weld Process Development

## *Al2219 to Al2219 Bounding Parameter DOE Results*

### Microstructural and Tensile Results for 0.400 gage




○ X-Ray Acceptable

X X-Ray Rejectable

# Weld Process Development

## Parameter DOE Results

### Room Temperature

| Run | Thickness | Ultimate (KSI) | | Yield (KSI) | | 2 inch Elong. (%) | |
|---|---|---|---|---|---|---|---|
| Number | (Inches) | Ave | std | Ave | std | Ave | std |
| 1 | 0.32 | 41.3 | 0.6 | 24.1 | 0.7 | 4.9 | 0.4 |
| 2 | 0.40 | 52.7 | 0.2 | 23.8 | 0.4 | 13.5 | 0.7 |
| 3 | 0.40 | 40.2 | 2.9 | 22.7 | 0.6 | 5.8 | 0.7 |
| 4 | 0.36 | 51.5 | 0.4 | 23.5 | 0.2 | 13.1 | 0.4 |
| 5 | 0.40 | 51.6 | 0.9 | 23.9 | 0.3 | 11.6 | 1.5 |
| 6 | 0.40 | 53.0 | 0.2 | 24.8 | 0.4 | 11.5 | 0.9 |
| 7 | 0.32 | 38.0 | 5.7 | 23.6 | 0.7 | 4.2 | 1.2 |
| 8 | 0.32 | 34.8 | 3.7 | 26.2 | 0.6 | 3.3 | 0.4 |
| 9 | 0.40 | 52.4 | 0.2 | 24.8 | 0.6 | 13.0 | 0.5 |
| 10 | 0.32 | 27.5 | 3.3 | 24.4 | 1.1 | 2.5 | 0.0 |
| 11 | 0.40 | 26.0 | 1.6 | 23.8 | 0.3 | 3.6 | 0.9 |
| 12 | 0.32 | 52.5 | 0.3 | 25.9 | 0.4 | 12.5 | 0.4 |
| 13 | 0.36 | 32.7 | 2.6 | 23.6 | 0.4 | 3.3 | 0.4 |
| 14 | 0.40 | 43.2 | 0.8 | 25.3 | 0.3 | 5.0 | 0.4 |
| 15 | 0.36 | 45.0 | 4.1 | 26.7 | 1.2 | 5.4 | 1.1 |
| 16 | 0.36 | 47.6 | 1.3 | 24.2 | 0.4 | 7.3 | 1.0 |
| 17 | 0.32 | 51.6 | 0.9 | 24.5 | 0.3 | 11.5 | 1.8 |
| 18 | 0.32 | 51.6 | 0.2 | 24.2 | 0.6 | 11.5 | 0.4 |
| 19 | 0.40 | 49.3 | 1.6 | 25.9 | 0.6 | 7.9 | 1.1 |
| 20 | 0.32 | 44.7 | 1.5 | 25.6 | 0.7 | 5.8 | 0.7 |
| 21 | 0.32 | 51.9 | 0.2 | 25.6 | 0.2 | 11.2 | 0.3 |
| 22 | 0.40 | 52.5 | 0.6 | 26.4 | 0.8 | 11.6 | 1.0 |
| 23 | 0.32 | 51.7 | 1.1 | 27.0 | 0.3 | 8.5 | 0.7 |

X-ray rejectable

### - 320 Degree F

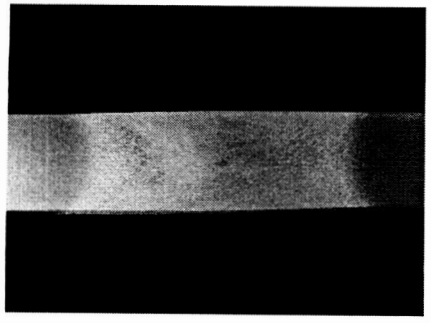
| Run | Thickness | Ultimate (KSI) | | Yield (KSI) | | 2 inch Elong. (%) | |
|---|---|---|---|---|---|---|---|
| Number | (Inches) | Ave | Ratio | Ave | Ratio | Ave | Ratio |
| 1 | 0.32 | 52.0 | 1.27 | 28.0 | 1.16 | 6.5 | 1.33 |
| 2 | 0.40 | 62.4 | 1.18 | 26.3 | 1.10 | 17.3 | 1.28 |
| 3 | 0.40 | 49.8 | 1.26 | 23.4 | 1.03 | 7.3 | 1.25 |
| 4 | 0.36 | 64.3 | 1.25 | 25.2 | 1.07 | 17.8 | 1.35 |
| 5 | 0.40 | 62.8 | 1.22 | 25.9 | 1.08 | 14.5 | 1.25 |
| 6 | 0.40 | 63.1 | 1.19 | 24.5 | 0.99 | 13.5 | 1.17 |
| 7 | 0.32 | 41.9 | 1.10 | 26.5 | 1.12 | 6.0 | 1.43 |
| 8 | 0.32 | 46.4 | 1.30 | 28.4 | 1.08 | 4.5 | 1.36 |
| 9 | 0.40 | 63.5 | 1.21 | 28.5 | 1.15 | 17.3 | 1.33 |
| 10 | 0.32 | 34.0 | 1.22 | 27.7 | 1.13 | 3.5 | 1.40 |
| 11 | 0.40 | 33.5 | 1.26 | 26.6 | 1.12 | 3.8 | 1.04 |
| 12 | 0.32 | 64.5 | 1.23 | 30.3 | 1.17 | 17.3 | 1.38 |
| 13 | 0.36 | 44.4 | 1.34 | 30.0 | 1.27 | 5.0 | 1.52 |
| 14 | 0.40 | 52.0 | 1.21 | 30.9 | 1.22 | 5.3 | 1.05 |
| 15 | 0.36 | 50.0 | 1.14 | 30.5 | 1.14 | 5.3 | 0.97 |
| 16 | 0.36 | 60.0 | 1.27 | 28.6 | 1.18 | 9.5 | 1.30 |
| 17 | 0.32 | 63.7 | 1.22 | 29.7 | 1.21 | 16.5 | 1.43 |
| 18 | 0.32 | 63.8 | 1.23 | 28.7 | 1.19 | 16.0 | 1.39 |
| 19 | 0.40 | 62.2 | 1.25 | 29.7 | 1.15 | 11.0 | 1.39 |
| 20 | 0.32 | 53.8 | 1.19 | 29.6 | 1.15 | 6.5 | 1.12 |
| 21 | 0.32 | 64.3 | 1.24 | 29.1 | 1.13 | 14.8 | 1.32 |
| 22 | 0.40 | 63.7 | 1.22 | 29.7 | 1.12 | 15.0 | 1.29 |
| 23 | 0.32 | 58.0 | 1.11 | 31.0 | 1.15 | 8.5 | 1.00 |

X-ray rejectable

# Weld Process Development

## *Al2219 to Al2219 Parameter DOE Verification*

0.320 Inch



Ultimate (KSI)/2" Elongation (%)

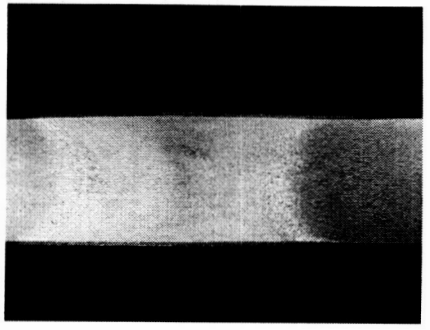
0.320 RT - 52.5 / 11.6

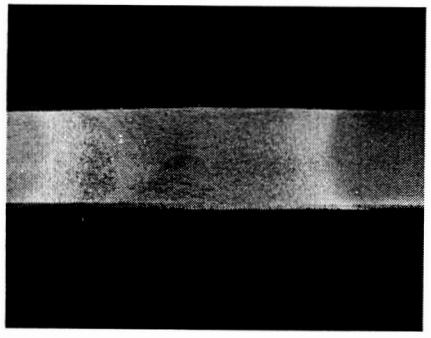
-320 - 64.7 / 15.5

0.400 RT - 52. 2 / 11.2

-320 - 60.0 / 15.3

0.400 Inch





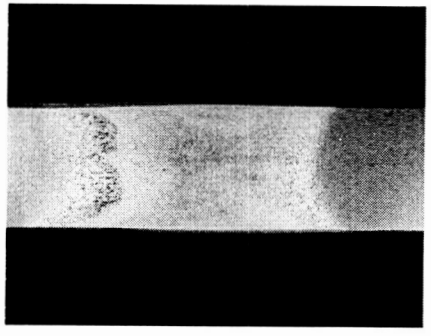
Ultimate (KSI)/2" Elongation (%)

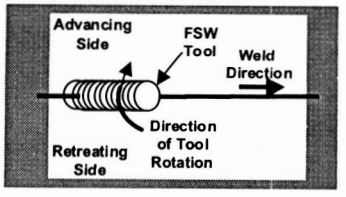
0.320 RT - 52.6 / 12.9

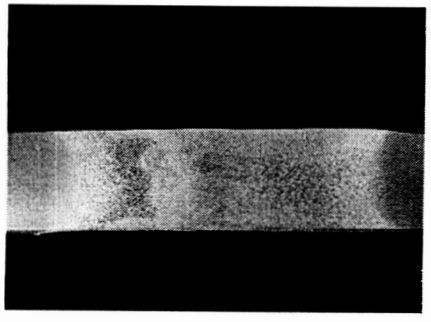
-320 - 63.9 / 16.3

0.400 RT - 52.9 / 13.5

-320 - 64.7 / 16.0





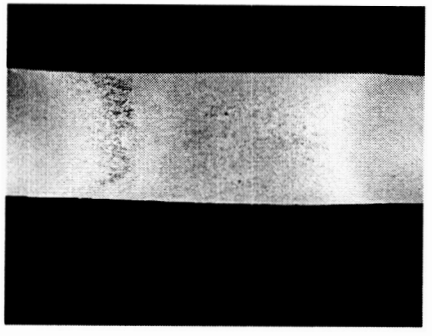
Ultimate (KSI)/2" Elongation (%)

0.320 RT - 48.8 / 7.7

-320 - 60.5 / 10.0

0.400 RT - 50.8 / 10.5

-320 - 58.5 / 10.9



# Weld Process Development

## *Al2219 to Al2219 Set-up DOE*

### Bounding Panels

| Trial | Centerline offset (Inches) | Gap (Inches) | Heat Input | Thickness (Inches) |
|---|---|---|---|---|
| 1 | Retreating | High | Minimum | 0.32 |
| 2 | Advancing | High | Minimum | 0.32 |
| 3 | Retreating | High | Maximum | 0.32 |
| 4 | Advancing | High | Maximum | 0.32 |
| 5 | Retreating | High | Minimum | 0.40 |
| 6 | Advancing | High | Minimum | 0.40 |
| 7 | Retreating | High | Maximum | 0.40 |
| 8 | Advancing | High | Maximum | 0.40 |

### DOE Panels

| Run Number | Trial | Centerline offset (Inches) | Gap (Inches) | Heat Input | Thickness (Inches) |
|---|---|---|---|---|---|
| 1 | 3 | Retreating | 0.000 | Maximum | 0.32 |
| 2 | 13 | 0 | Mean | Maximum | 0.40 |
| 3 | 7 | Retreating | 0.000 | Maximum | 0.40 |
| 4 | 11 | Advancing | High | Minimum | 0.36 |
| 5 | 20 | Advancing | Mean | Minimum | 0.40 |
| 6 | 15 | 0 | High | Nominal | 0.40 |
| 7 | 18 | Retreating | 0.000 | Nominal | 0.32 |
| 8 | 2 | Retreating | High | Minimum | 0.32 |
| 9 | 5 | Advancing | 0.000 | Minimum | 0.40 |
| 10 | 2 | Retreating | High | Minimum | 0.32 |
| 11 | 14 | Retreating | Mean | Nominal | 0.40 |
| 12 | 4 | Advancing | High | Maximum | 0.32 |
| 13 | 10 | Retreating | 0.000 | Minimum | 0.36 |
| 14 | 6 | Retreating | High | Minimum | 0.40 |
| 15 | 9 | Retreating | High | Maximum | 0.36 |
| 16 | 12 | Advancing | 0.000 | Maximum | 0.36 |
| 17 | 19 | Advancing | Mean | Maximum | 0.32 |
| 18 | 1 | Advancing | 0.000 | Minimum | 0.32 |
| 19 | 16 | 0 | 0.000 | Minimum | 0.40 |
| 20 | 3 | Retreating | 0.000 | Maximum | 0.32 |
| 21 | 1 | Advancing | 0.000 | Minimum | 0.32 |
| 22 | 8 | Advancing | High | Maximum | 0.40 |
| 23 | 17 | 0 | High | Minimum | 0.32 |

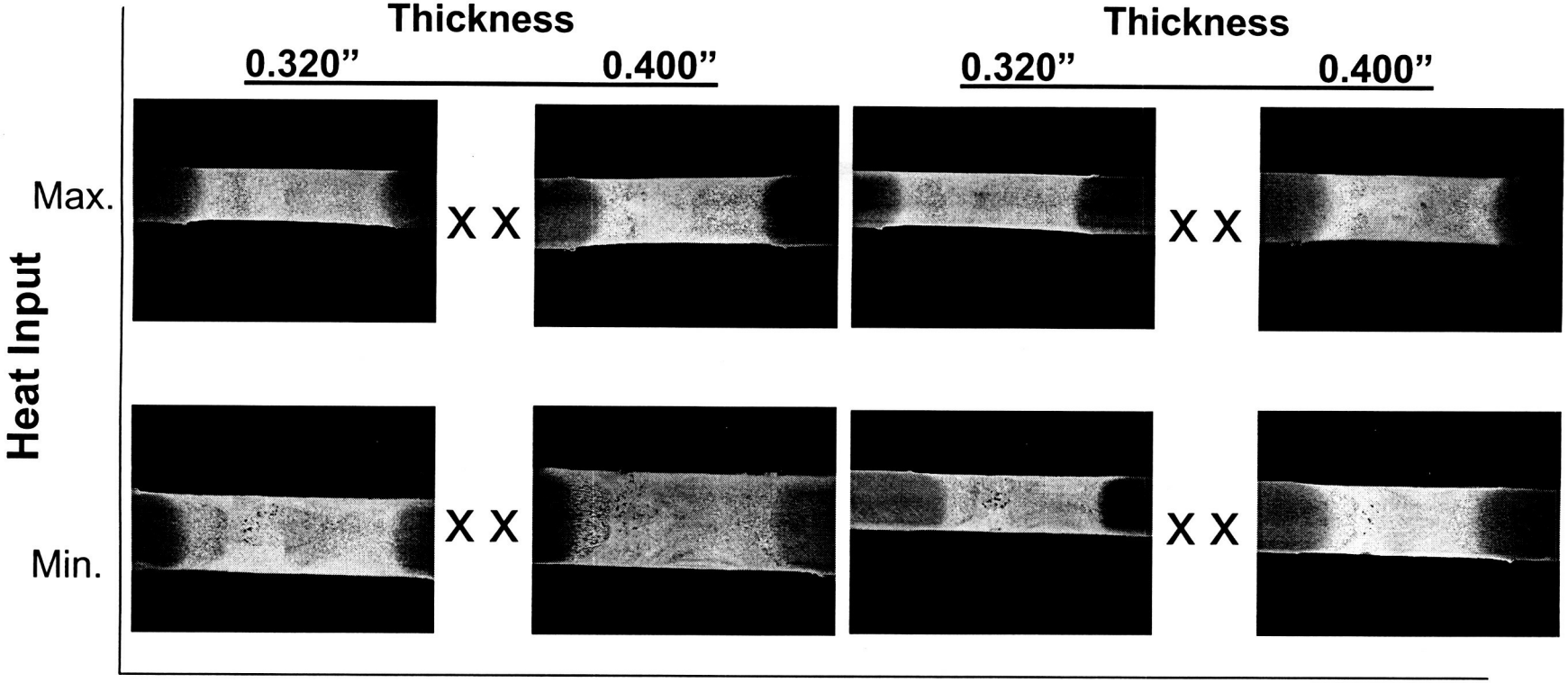
### Verification Panels

| Trial | Centerline offset (Inches) | Gap (Inches) | Heat Input | Thickness (Inches) |
|---|---|---|---|---|
| 1 | Maximum | Maximum | Minimum | 0.32 |
| 2 | Maximum | Maximum | Maximum | 0.32 |
| 3 | Maximum | Maximum | Minimum | 0.40 |
| 4 | Maximum | Maximum | Maximum | 0.40 |

# Weld Process Development

## *Al2219 to Al2219 Set-up Bounding DOE*

### Microstructural and Tensile Results with Weld Joint Gap – High




Minimum
Rotation / Travel / Load
Min / Max / Min

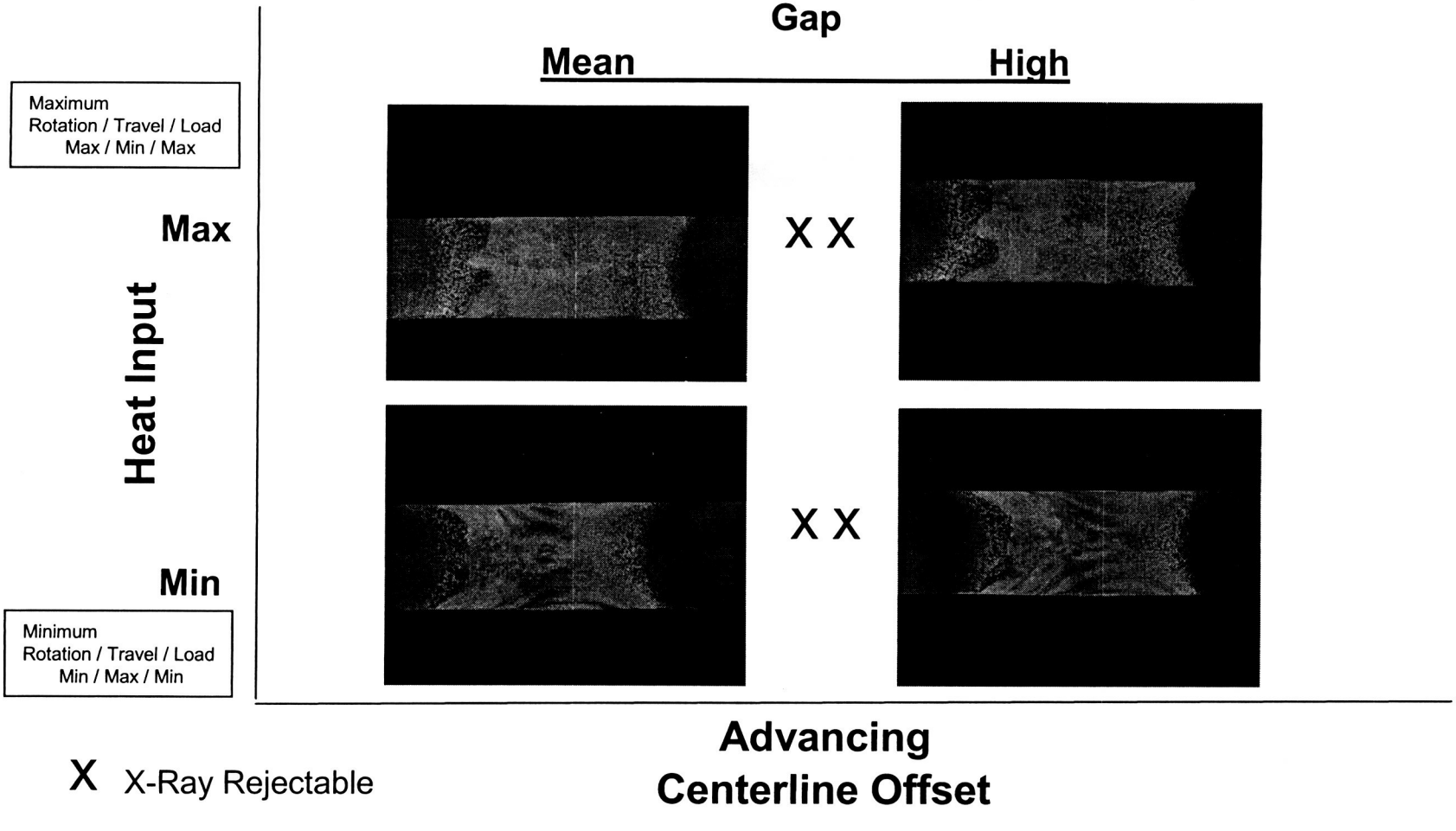
Maximum
Rotation / Travel / Load
Max / Min / Max

**X:** X-Ray Rejectable

# Weld Process Development

## *Al2219 to Al2219 Set-up Bounding DOE*

### Microstructural and Mechanical Property Results - 0.400 gage

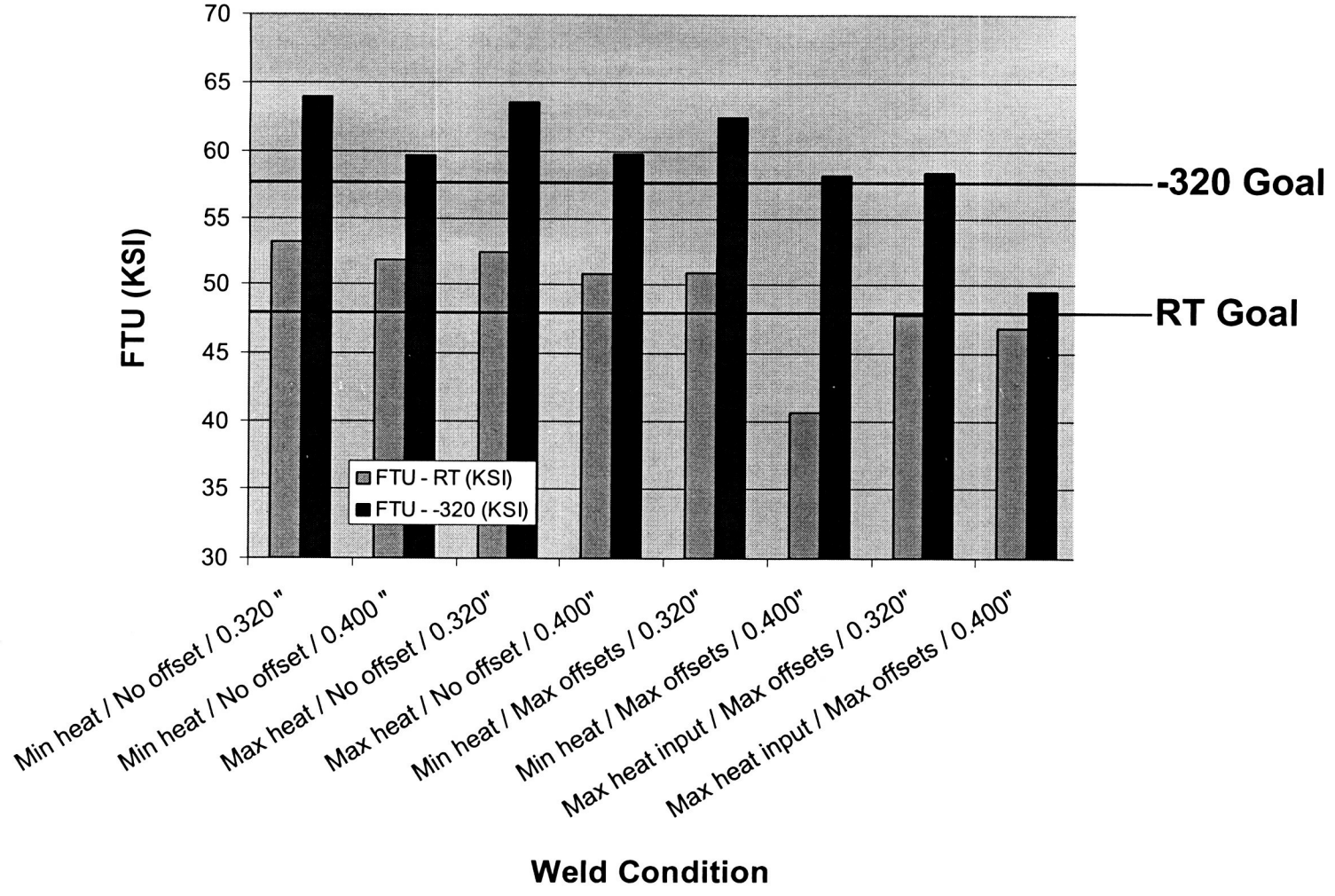



X X-Ray Rejectable

# Weld Process Development

## *Al2219 to Al2219 Set-up Verification DOE*

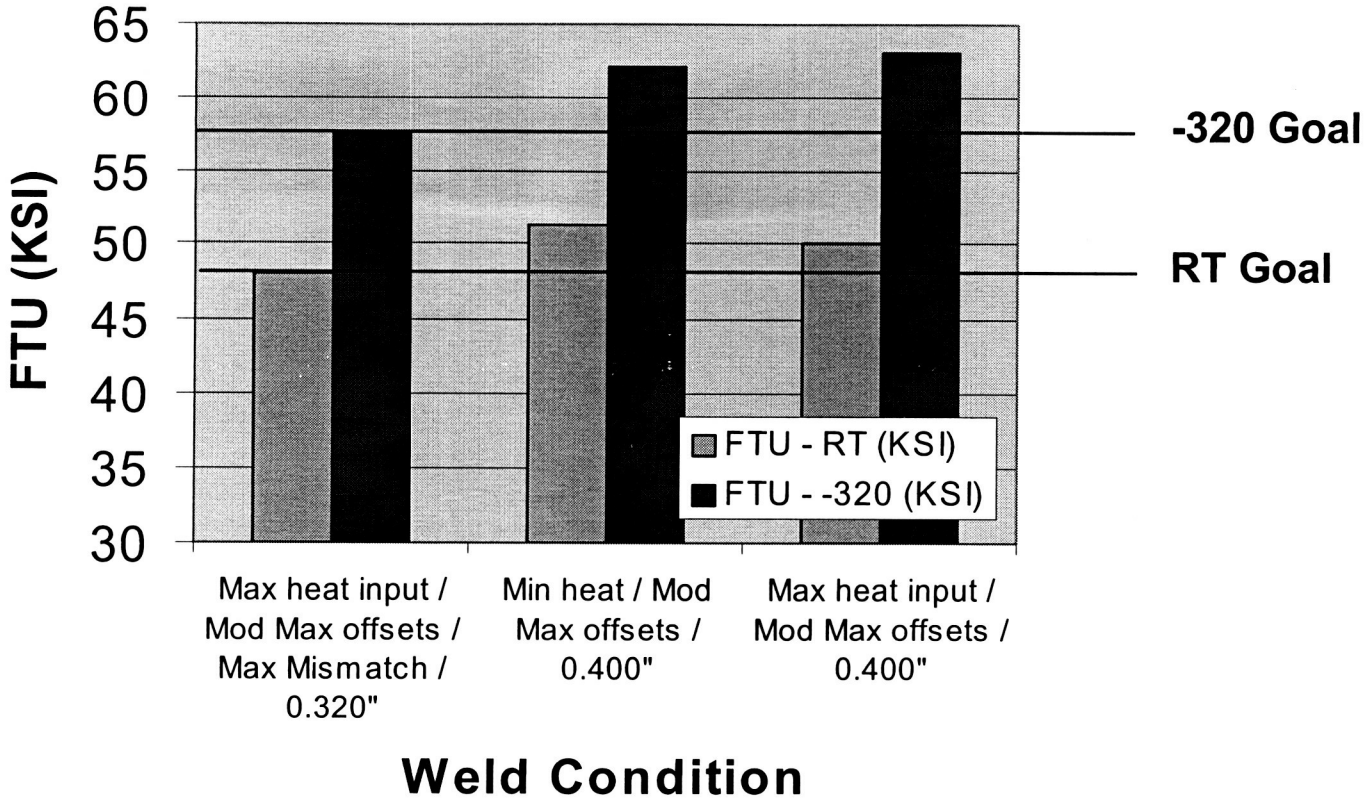
- **Parameter Operating Box Verification**



# Weld Process Development

## *Additional Al2219 to Al2219 Testing*

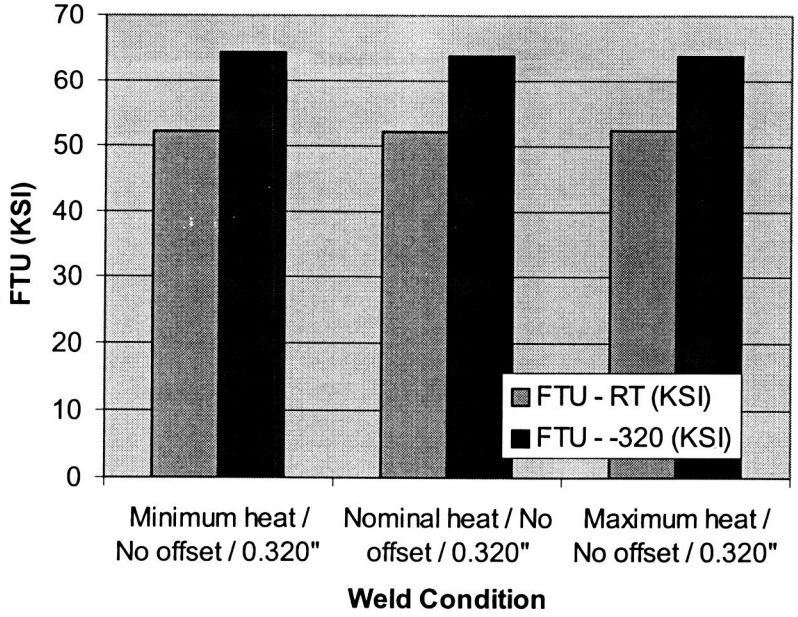
### Modified Operating Box



# 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**

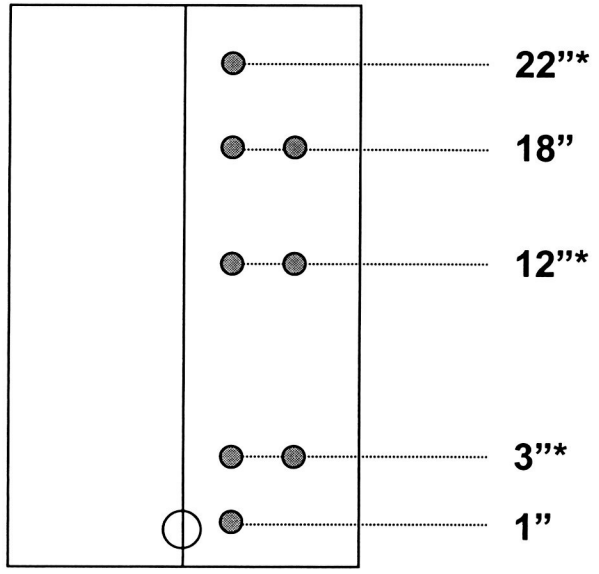
# Weld Process Development

## *Al2219 to Al2219 DOE Supplemental Testing*

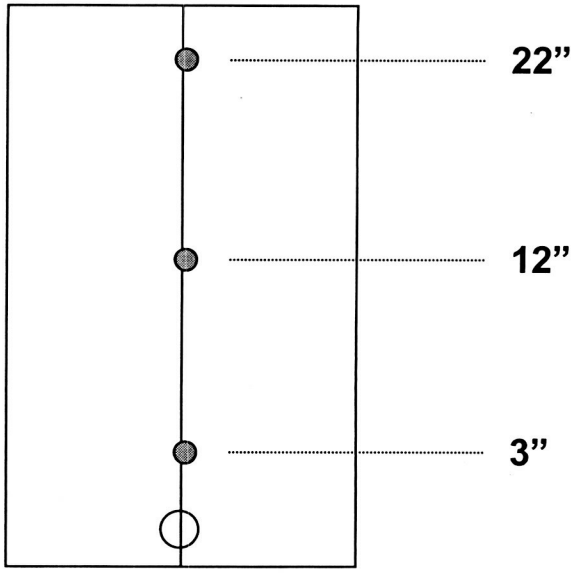
### Temperature Measurements

**Perform the following temperature measures on the min and max weld schedules in 0.320" 2219 to 2219 (6"x24" panels)**

**Surface Measurements**
**Top and Bottom**
**0.100 inches from shoulder (0.700 inches from weld centerline)**
***Second measure 3 inches from weld centerline**
**(K Thermocouple)**




**Centerline Measurements**
**0.050 inches max. from weld centerline**

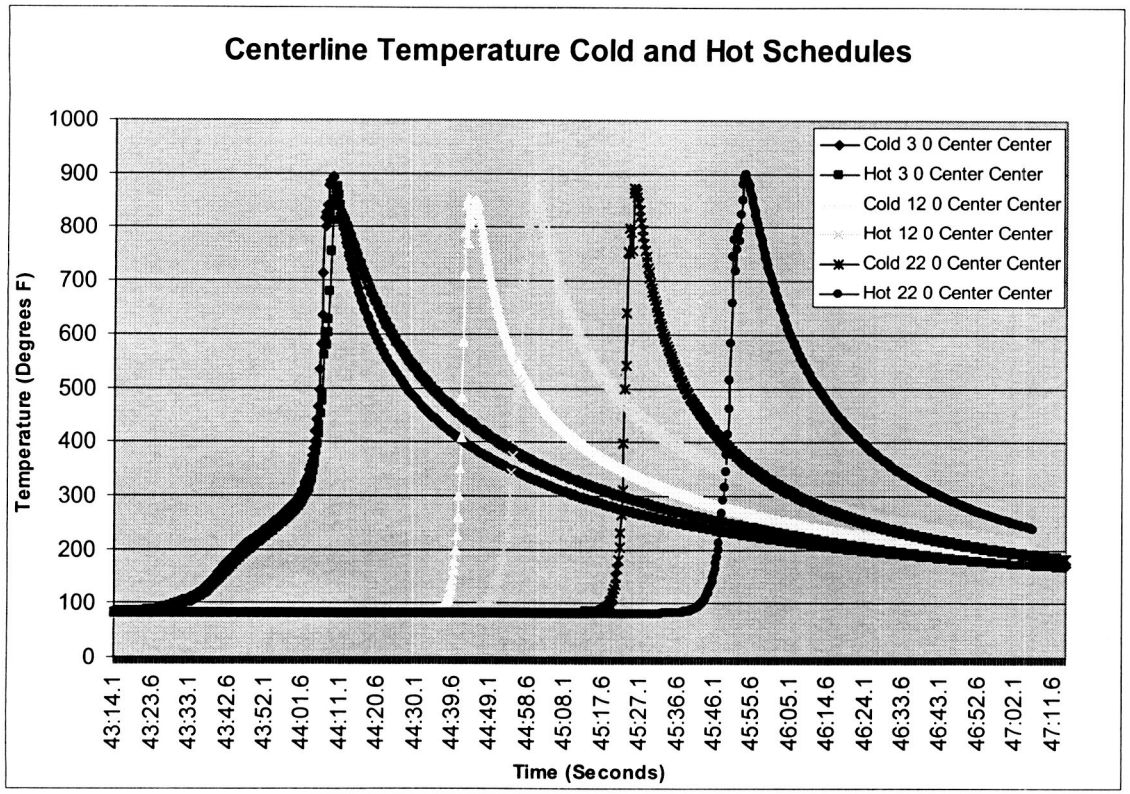


# Weld Process Development

## *Al2219 to Al2219 DOE Supplemental Testing*

### Temperature Measurements - Centerline - Max and Min Schedules

- Data indicates that heating starts approximately 2.5 inches ahead of the weld
- The dips in the heat profile are most likely due to closing of the hole for the thermocouples causing the thermocouple wires to connect at a different location

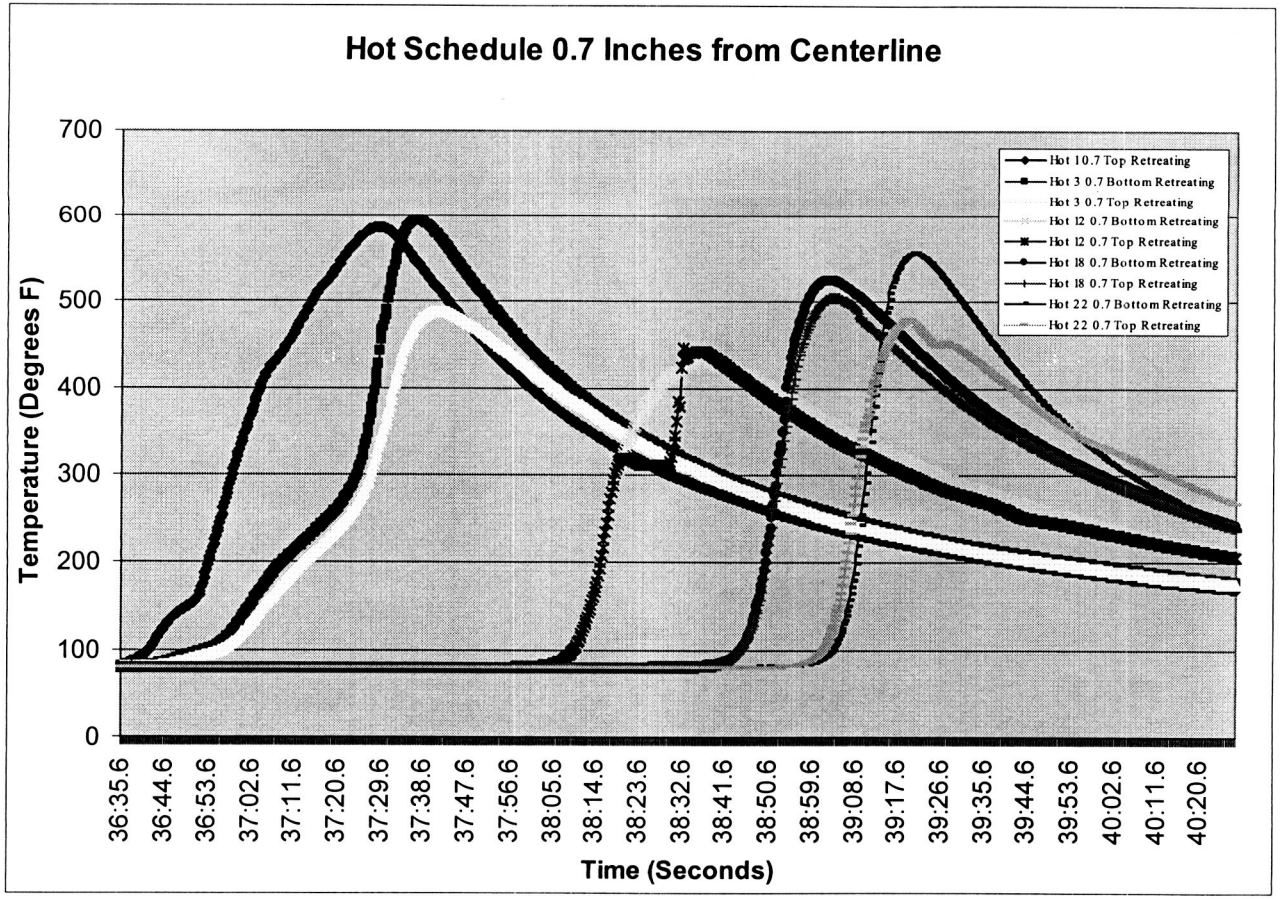


# Weld Process Development

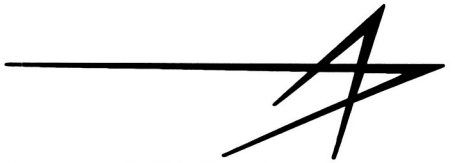
## *Al2219 to Al2219 DOE Supplemental Testing*

### Temperature Measurements - 0.7 inch from Centerline - Max Schedule

- Data indicates the coldest location is near the center of the 24" test panel
- The dips in the heat profile are from thermocouples coming loose during welding



# Weld Process Development



## *Al2219 Design of Experiments Summary*

- Al2219 to Al2219 DOE's are complete
  - Ambient and LN2 temperature strength goals have been achieved
  - Microstructure verifies defect free weld joints
  - Radiography and visual inspection were adequate to detect anomalies

- Operating Box for the Intermediate Scale demonstration has been established
  - Gap, mismatch and centerline offset limits are reasonable

- Supplemental testing to tacking and assess temperature
  - Tacking had no effect on the self-reacting weld strength
  - Temperature readings confirm solid state, localized heating