Friction Stir Process Mapping Methodology

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• Friction Stir Welding (FSW)
  – FSW is a solid-state process using a rotating tool with a shoulder and a projecting pin.
  – The pin tool is rotated and plunged into the joint until the shoulder contacts the top surface.
  – The frictional heating between the pin tool and the joint plasticizes the material in the local region near the pin.
  – The material at the weld centerline is joined through a combination of forging processes that occurs in the local region of the pin tool.
  – Three significant parameters: spindle speed, travel speed, plunge load or plunge position.
FSW Process Maps

- A process map summarizes the weld process performance for a given pin tool geometry and joint configuration.
- Targeting a consistent penetration ligament, the process is simplified into two parameters: travel speed and rotation speed.
- Other parameters, such as plunge force, traverse force, weld nugget geometry, NDE response, and mechanical properties are assumed to be dependent variables.

- **YELLOW**: Unusual flow patterns, unstable position and process loads, excessive flash, poor mechanical properties
- **GREEN**: Symmetric flow patterns, stable position and process loads, good strength
- **RED**: NDE rejections, volumetric defects, poor strength, excessive process loads
• A selected rpm/ipm combination (weld schedule) provides a specific nugget geometry, heat input, and mechanical strength.
• The selected nominal weld schedule, or sweet spot, is the best compromise between process stability, mechanical strength, NDE response, and machine capability.
• Once the nominal schedule is selected, process loads and heel positions are explored to determine their acceptable operating windows.
• Statistical process control in conjunction with the process map data provides quality control and grounds for reduced NDE requirements.
FSW Process Maps

- Methodology Overview

Determine joint configuration, pin tool design, anvil and clamping system

Phase I Quick Look

Phase II Testing

Select weld schedule

Characterize process with nominal weld schedule
Phase I Quick Look

• The “quick look” provides a general overview of the process map
  – Three weld schedules are performed on a 24 inch long test panel
  – Weld schedules are performed “hot” to “cold” by changing the travel speed (constant rotation speed)
  – Metallographic samples are excised near the end of each weld schedule

![Diagram of weld schedules]

<table>
<thead>
<tr>
<th>Schedule #1</th>
<th>Schedule #2</th>
<th>Schedule #3</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.0&quot;</td>
<td>6.0&quot;</td>
<td>14.0&quot;</td>
</tr>
<tr>
<td>Macro 1</td>
<td>Macro 2</td>
<td>Macro 3</td>
</tr>
<tr>
<td>16.0&quot;</td>
<td>11.0&quot;</td>
<td>16.0&quot;</td>
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<tr>
<td>24&quot;</td>
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<td></td>
</tr>
<tr>
<td>Weld Start</td>
<td>4.0&quot;</td>
<td>6.0&quot;</td>
</tr>
</tbody>
</table>
Phase I Quick Look

- Yellow, Green, and Red regions are delineated based on the metallographic data from the Quick Look welds.

![Graphs showing Friction Stir Process Mapping Methodology for different conditions: Thin gauge Similar Alloy, Thick gauge Similar Alloy, Thin gauge Dissimilar Alloy, Thick gauge Dissimilar Alloy.](image)
Phase I Quick Look

- Thin gauge similar alloy configuration
  - Low (A), medium (B), and high (C) heat input

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Phase I Quick Look

- Thin gauge similar alloy configuration
  - Heel plunge vs. travel rate
Phase I Quick Look

- Thin gauge similar alloy configuration
  - Scaling/ Galling
Phase I Quick Look

- Thin gauge similar alloy configuration
  - Large Weld Nugget and Excessive Flash
Phase I Quick Look

- Thin gauge similar alloy configuration
  - Root voids and “worm holes”
Phase I Quick Look

- Thick gauge similar alloy configuration
  - Low (A), medium (B), and high (C) heat input
Phase I Quick Look

- Thin gauge dissimilar alloy configuration
  - Low (A), medium (B), and high (C) heat input
Phase I Quick Look

- Thin gauge dissimilar alloy configuration
  - Root void and “worm hole”
Phase I Quick Look

- Thin gauge dissimilar alloy configuration
  - Irregular nugget flow
  - Location of particular alloy influences flow within the nugget

Reversed alloy locations
Phase I Quick Look

- Thick gauge dissimilar alloy configuration
  - Low (A), medium (B), and high (C) heat input
Phase I Quick Look

- Thick gauge dissimilar alloy configuration
  - High heat input weld/ collapse weld nugget with “worm holes”
Phase I Quick Look

- Thick gauge dissimilar alloy configuration
  - Low Heat Input Weld with “Worm Holes”
Phase II Testing

- Weld schedules that provide acceptable metallographic profiles from Phase I are performed on 24” long test panels.
  - The longer weld provides adequate time for weld to reach stability
    - More reliable NDE response and tensile tests
  - Process load data becomes more consistent
- Tensile tests are conducted at the expected service temperatures of the weld
- These tests define the process envelope and begin to focus in on the “sweet spot”

12”x24” Test Panel
Phase II Testing

- The process envelope is delineated using the Phase II test data
  - Mechanical strength, NDE, and tool performance are factors to consider

![Graphs showing process envelopes for different conditions: Thin gauge Similar Alloy, Thick gauge Similar Alloy, Thin gauge Dissimilar Alloy, Thick gauge Dissimilar Alloy.](image)
Phase II Testing

- Tensile strength increases with faster travel speeds
  - Cryogenic strength is more sensitive than room temperature strength to heat input
- Process loads, especially traverse loads, increase with travel speed
- The ability to perform cold welds depends on the machine’s control system response
Weld Schedule Selection

• Schedule selection is the best compromise between the following factors:
  – Process stability
  – Mechanical strength
  – NDE response
  – Machine capability

• The nominal schedule should be near the center of the process envelope to ensure robust performance to variations in the manufacturing environment

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Multiple welds are performed with varied setup conditions
Process information, such as plunge load, is collected and acceptable bounds are established
FSW Process Map Summary

- The weld process performance for a given weld joint configuration and tool setup is summarized on a 2-D plot of RPM vs. IPM.
- A process envelope is drawn within the map to identify the range of acceptable welds.
- The sweet spot is selected as the nominal weld schedule.
- The nominal weld schedule is characterized in the expected manufacturing environment.
- The nominal weld schedule in conjunction with process control ensures a consistent and predictable weld performance.