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
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.
• 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
• 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 and metallographic samples](image)
metallurgical data from the Quick Look Welds. Yellow, Green, and Red regions are delimited based on the phase I Quick Look.
Phase I Quick Look

- Thin gauge similar alloy configuration
  - Low (A), medium (B), and high (C) heat input
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
Large Weld Nugget and Excessive Flash

Thin gauge similar alloy configuration

Phase 1 Quick Look
Phase I Quick Look

- Thin gauge similar alloy configuration
  - Root voids and "worm holes"

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Phase I Quick Look

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

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

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

Reversed alloy locations

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Low (A), medium (B), and high (C) heat input

Thick gauge dissimilar alloy configuration

Phase I Quick Look
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"

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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
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.
Process Characterization

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

![Graph showing plunge force vs. weld position](image)

<table>
<thead>
<tr>
<th>Weld Position (in)</th>
<th>Plunge Force (lbf)</th>
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<tbody>
<tr>
<td></td>
<td>Average</td>
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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