Friction Stir Welding of Ferritic Steel

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Outline

• FSW
• FSW of High Temperature Materials
• Approach-Material/Equipment/Analysis
• Results
  – Process Window
  – Microstructure
  – Mechanical Properties
  – PCBN tool life
• Summary
Friction Stir Welding

- Patented by TWI in 1991
- Solid-state
  - No solidification defects
  - Reduced thermal effect from lower peak temperatures
- Less distortion
- No fumes
FSW of High Temperature Materials

- Strong Interest in FSW of HTM
  - DUST (ONR)
  - MAI (AFOSR)
  - TWI (GSP)
- Benefits Thought to Exceed Those of FSW in Aluminum Alloys
  - Less Distortion
  - No Hazardous Fumes (Hex-Cr, Mn)
  - No Solidification Defects
Limitations

• Tool Life
  – Suitable Tool Material
    • High Temperatures
    • Chemical Wear
    • Mechanical Wear
  – Metallic Tools Have Demonstrated Good Weld Quality and Sound Properties

• Developments in PCBN Tooling
  – Polycrystalline Cubic Boron Nitride
    • Synthetic Super-Abrasive
    • Developed in Cooperation with Advanced Metal Products
    • Tool Life in Excess of 80 m (260’)

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FSW Procedure

- 6 mm thick HSLA-65 of nominal composition: 0.1C max., 1.10-1.65Mn, 0.025P max., 0.01S max., 0.1-0.5Si, 0.4Ni max., 0.2Cr max., 0.08Mo max., 0.35Cu max., 0.10V max., 0.05Nb max., 0.08Al max
- FSW was performed on a custom designed CNC machine
  - 30 horsepower with full data acquisition system
- The tool material:
  - polycrystalline cubic boron nitride (PCBN) FSW tooling™
  - 25 mm diameter shoulder, 4.8 mm pin length, 4° tilt from normal
- A process parameter window was established
  - FSW parameters for post weld microstructure and mechanical properties characterization were selected from PW
- All welds were sectioned and polished for optical metallography. The sections were final polished with 3 μm diamond paste, and etched with a 2% Nital solution
- Vickers microhardness traverse was made at the weld centerline of select welds at 1000-gram load
- TEM foils were removed from select regions for preliminary analysis of the FSW microstructure
FSW Equipment

• Equipment used for FSW
### HSLA 65 Process Window

**Weld surface 650 RPM 6 IPM**

<table>
<thead>
<tr>
<th>Rotation speed (RPM)</th>
<th>Travel speed (rpm, ipm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>350</td>
<td>5 (2)</td>
</tr>
<tr>
<td>450</td>
<td>7.6 (3)</td>
</tr>
<tr>
<td>550</td>
<td>10.2 (4)</td>
</tr>
<tr>
<td>650</td>
<td>12.7 (5)</td>
</tr>
<tr>
<td>750</td>
<td>15.2 (6)</td>
</tr>
<tr>
<td>10000 lbs-f Z</td>
<td>17.8 (7)</td>
</tr>
<tr>
<td>10500 lbs-f Z</td>
<td>20.3 (8)</td>
</tr>
<tr>
<td>11000 lbs-f Z</td>
<td></td>
</tr>
</tbody>
</table>

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HSLA 65 Process Window

Next Trials
Smooth surface
Poor surface
With holes

Rotation speed (RPM)

Travel speed (IPM)

10000 lbs-f Z
10500 lbs-f Z
10500 lbs-f Z
11000 lbs-f Z

11000 lbs-f Z
HSLA 65 Process Window

- HSLA-65 has been successfully FSW over a wide range of parameters
- Process window was limited by the amount of applied torque that the tool would allow.
  - Parameters performed at high spindle speeds and travel rates required large Z axis loads and higher torque values on the tool.
    - Premature failure of the tools was encountered
    - Tool design changes needed in mechanical holding of PCBN and pin geometries in order for a broader process window to be utilized
FSW Microstructure in HSLA

750 rpm and 6 ipm (all micrographs at 500X)
Microstructure (overview)

550 rpm, 5 ipm (all micrographs at 500X)
Microstructure (BM)

Optical micrographs

200x

500x

Low magnification

Dislocations

Bainite

TEM micrographs

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Microstructure (HAZ 2)

Optical micrographs

200x

500x

Low magnification

Dislocations

TEM micrographs

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Microstructure (Center)

Optical micrographs

200x

500x

Low magnification

Dislocations

TEM micrographs

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Microstructure (AS)

Optical micrographs

TEM micrographs
Microhardness Comparison

- Width of the Stir Zone increases with RPM and Travel
- Peak hardness increases with increasing RPM
Mechanical Properties

- All weld metal YS/UTS ratio higher than base metal
- All weld metal YS equivalent to base metal YS

<table>
<thead>
<tr>
<th>Weld</th>
<th>YS MPa (Ksi)</th>
<th>UTS MPa (Ksi)</th>
<th>% Elong.</th>
<th>% R.A.</th>
</tr>
</thead>
<tbody>
<tr>
<td>FSW HSLA-65 All weld metal</td>
<td>596.6 (86.6)</td>
<td>788.2 (114.4)</td>
<td>14.5</td>
<td>76.8</td>
</tr>
<tr>
<td>HSLA-65 Base Metal</td>
<td>604.9 (87.8)</td>
<td>673.2 (97.7)</td>
<td>18.7</td>
<td>80.8</td>
</tr>
<tr>
<td>Weld Metal ASTM A945</td>
<td>447-551 (65-80)</td>
<td>482 (70) min.</td>
<td>22 min</td>
<td>----</td>
</tr>
<tr>
<td>Base Metal ASTM A945</td>
<td>447 (65) min.</td>
<td>537-689 (78-100)</td>
<td>22 min.</td>
<td>---</td>
</tr>
</tbody>
</table>

*Mechanical Properties from: M. Possada, et.al. Thermec 03, Madrid, Spain
FSW Tool Life Test in HSLA-65

- Tool life currently at 9 m (30 feet)
- Life test performed in HSLA 65
- Welds produced in 40 inch lengths
- Parameters: 650 RPM, 5 IPM
- Tool failure by fracture not wear
  - Fracture promoted by rotation of PCBN in collar
  - Expect tool life in excess of 150 m (500ft) with collar redesign

Figure showing setup and welding during HSLA 65 life test.
FSW Tool Life Test

- Tool failure occurred at 30 feet, with the pin fracturing just before extraction on the 9th pass.
- Tool geometry changes needed in order to increase tool life
  - Mechanical holding of the PCBN in tool
  - Pin geometries that allow for lower Z and X axis loads
Summary

- HSLA-65 was successfully welded over a wide range of tool rotation and travel speeds; 450-750 RPM and 7.6-18 cpm.
- YS and UTS (596.6 MPa and 788.2 MPa, respectively) in the as-FSWed condition exceeds the base metal properties.
- The weld nugget exhibits an increase in hardness (20 DPH) relative to the base metal.
- There is a hardness band which persists near the advancing side of the weld which is substantially harder (80-100 DPH) than the reset of the nugget. The location and maximum hardness of this band changes with weld parameters which is likely due to the change in location of peak temperature and subsequent cooling rate.

- Additional parameter/microstructure/mechanical property characterization needed!!!!!!!!!!