Friction Stir Welding of High Temperature Materials

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- Time on FSW machines provided by Boeing Huntington Beach and MTS Corporation
Presentation Topics

- PCBN Overview
- Tool Design
- Tool Materials and Life
- Weld Properties
- FSW Machine Evaluations
- Future Plans
Polycrystalline Cubic Boron Nitride (PCBN)

- Second in hardness only to diamond
- Diamond crystal structure, with C and B occupying alternate lattice sites
- CBN powder Created in HT-UHP presses (1700 K, 6,000 MPa)
- CBN powder sintered in HT/UHP press to form polycrystalline blank
Tool Materials

- **MN100**
  - High PCBN content
  - Difficult to machine
  - Expensive

- **MN50**
  - Lower PCBN content
  - Easier to machine (e.g., EDG possible)
  - Less expensive
PCBN Properties

- Hard, wear resistant, survives temperatures to 1500 K
- Chemically inert
- Poor tensile strength, low toughness
- Difficult to manufacture
- Limited to relatively small pieces
- High thermal conductivity
Specific Tool Design

- 19 mm WC shank
- 19-25 mm φ CBN disk
- 6° face angle
- Pin L/D about 0.5
  - Lengths up to 6 mm
- Radii about 1 mm
- Pin
  - Smooth for short pins
  - Flats on end for long pins
Managing Thermal Load

- Stainless steel: 15 W/m-K
- PCBN: 250-300 W/m-K
- WC: 70 W/m-K
- More heat flows into tool holder than weld!
- Need for insulator to keep heat in weld zone
- Need to protect machine bearings
Tecnara Tool Holder

- Chilled water-glycol recirculator on shank
- Air/gas cooling on locking collar
- Fits in milling machine (#50 Taper)
- Instrumented for tool temperature
- Very low runout -- 0.005 mm (0.0002") at 20 cm (8") below holder
FSW of Stainless Steel
A Completed Weld
Tool Materials

- Fabricate tools from MN100 and MN50
- Test weld on 6mm 316L plate
- MN100 has clearly superior life, but MN50 works also
- Potential for intermediate material
  - Future program
Tool Life

- Failure Mechanisms
  - Wear when temperature is too high or too low
  - Pin fracture when retracting tool
  - Shoulder fracture during welding

- Fracture elimination
  - Tool redesign
  - Better process control
  - Design of custom CBN grades
Tool Wear-- Before and After
Recent Tool Life Results

- Tool life is currently in excess of 13 m
- Fractures continue, but current failure mode is wear due to improper welding parameters
Materials Welded -- Short Pin
(approx. 2.5 mm)

- 1.5 mm 301L stainless
- 3.2 mm 316L stainless
- 6.4 mm 316L stainless (two-sided weld)
- 3 mm Invar
Materials Welded -- Long Pin (4.5- 6 mm)

- 6.4 mm 316L stainless
  - single-sided weld, good properties
- 7 mm AL6XN stainless
  - two-sided weld, pin channel heals, then cracks
  - Ran tool for 40 minutes (0.5 ipm), then ran weld in hi hard armor
- 6.4 mm Hi-Hard Armor Plate
  - both two-sided weld and one sided weld
- 6 mm Invar
  - Single sided
- 6 mm Cu-Ni-Cr
  - Single sided
FSW Hi-Hard Plate

6 mm Thick
Weld Characterization: Hi-Hard Armor

- 6 mm single sided full penetration weld
  - Fully consolidated weld
## Tensile Properties in Hi-Hard Armor

<table>
<thead>
<tr>
<th>Property</th>
<th>Yield Strength</th>
<th>UTS</th>
<th>Elongation</th>
</tr>
</thead>
<tbody>
<tr>
<td>As Received</td>
<td>204 ksi</td>
<td>248 ksi</td>
<td>9.5%</td>
</tr>
<tr>
<td></td>
<td>1400 MPa</td>
<td>1710 MPa</td>
<td></td>
</tr>
<tr>
<td>Weldment</td>
<td>151 ksi</td>
<td>178 ksi</td>
<td>2.6%</td>
</tr>
<tr>
<td></td>
<td>1040 MPa</td>
<td>1230 MPa</td>
<td></td>
</tr>
<tr>
<td>Ratio</td>
<td>74%</td>
<td>71%</td>
<td>27%</td>
</tr>
</tbody>
</table>

Failure in HAZ, advancing side
Microhardness

As
Received
Hardness: 527 HV
Failed Specimen
FSW Machine Evaluation

- ESAB SuperStir
  - Boeing Huntington Beach
- MTS FSW PDS
  - MTS, Eden Prairie MN
- Evaluate welds on a variety of high-temperature materials
316L Stainless Steel

- Boeing Huntington Beach
- Varying Parameters

Courtesy: Doug Waldron and Keith McTiernan, The Boeing Company, Huntington Beach, CA
316L Stainless Steel

- Boeing Huntington Beach
  - Force control
  - Excellent welds

*Courtesy: Doug Waldron and Keith McTiernan, The Boeing Company, Huntington Beach, CA*
Cu-Ni-Cr Alloy

Courtesy: Doug Waldron and Keith McTiernan, The Boeing Company, Huntington Beach, CA
FSW Machines for High Temperature Materials

- **Strengths of existing FSW Machines**
  - Measurement capabilities
  - Automatic operation

- **Concerns**
  - Spindle runout
  - Shock response
  - Response time for making changes
  - Load capacity/Rigidity -- 8500 lbf axial for welding
  - Consistent thermal environment
Summary

- PCBN works well on ferrous materials
  - In excess of 50 feet of weld per tool
- Welds made in variety of materials
  - 3 mm 316 L, 6 mm Hi-Hard Armor, HSLA 65 successful
  - 6 mm 316L, 6 mm AL6XN need more work
- Getting a better handle on PCBN/base materials
  - HSLA 65, 316L, Hi Hard Armor, A-36 steel
- Operating window of PCBN
  - Within it, EXCELLENT tool life
  - Boundaries need definition
- FSW Machine tools
  - Need to better define requirements
  - Spindle quality is critical for HTM
Questions/Discussion
Future Plans

Need to focus

◆ Select a candidate material, HSLA 65
  – Continue evaluate 6.4 mm one-sided weld in HSLA 65
◆ Tool development
  – Need to define operating window of PCBN
  – Need to determine tool life
◆ Process Development
  – Implement tool thermal instrumentation
  – Define process parameters to stay within tool operating window
  – Etc…..
Manufacturing Process

- Metals: Machining
- Superabrasives: Net shape or grinding
- Our tools: diamond grinding from PCBN blank
- Future potential -- EDG
Supporting Loads

- Thrust up to 50 kN
  - WC Shank
- Lateral -- several kN
  - Superalloy locking collar (Rene 41)
- Torque
  - Flats on locking collar
Thermal Modeling

- One-Dimensional, Steady-State Model
- Heat flow only in axial direction
- Conduction only -- no convection or radiation
- Interfacial resistance ignored
- Constant weld temperature, shank temperature
## Material Properties

<table>
<thead>
<tr>
<th>Material</th>
<th>Thermal Conductivity, W/m-K</th>
</tr>
</thead>
<tbody>
<tr>
<td>CBN</td>
<td>250</td>
</tr>
<tr>
<td>WC</td>
<td>70</td>
</tr>
<tr>
<td>Titanium</td>
<td>10</td>
</tr>
<tr>
<td>Ceramic</td>
<td>1</td>
</tr>
<tr>
<td>Rene 41</td>
<td>23</td>
</tr>
</tbody>
</table>
Model Results

Predicted Tool Temperatures

Distance from Weld Surface, mm

Temperatures, °C

Titanium, 0.25 mm
Titanium, 0.5 mm
Ceramic, 0.5 mm
Rene 41, 1 mm
Predicted Heat Flux and Temperature

- 1200°C tool surface temperature, 100°C shank surface temperature, 0.5 mm insulator

<table>
<thead>
<tr>
<th>Material</th>
<th>Conductivity (W/mK)</th>
<th>Insulator T (°C)</th>
<th>Shank T (°C)</th>
<th>Q (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Titanium</td>
<td>10</td>
<td>1166</td>
<td>1035</td>
<td>595</td>
</tr>
<tr>
<td>Rene 41</td>
<td>23</td>
<td>1164</td>
<td>1103</td>
<td>635</td>
</tr>
<tr>
<td>Tungsten</td>
<td>130</td>
<td>1162</td>
<td>1151</td>
<td>668</td>
</tr>
<tr>
<td>Fused Quartz</td>
<td>3.4</td>
<td>1173</td>
<td>860</td>
<td>483</td>
</tr>
</tbody>
</table>
Tool Life

- Failure Mechanisms
  - Wear
  - Pin fracture
  - Shoulder fracture

- Fracture elimination
  - Tool redesign
  - Better process control
  - Design of custom CBN grades
# Preliminary Tool Life Results

<table>
<thead>
<tr>
<th>Tool</th>
<th>Life</th>
<th>Failure Mechanism</th>
</tr>
</thead>
<tbody>
<tr>
<td>2,3</td>
<td>60 cm</td>
<td>Fracture</td>
</tr>
<tr>
<td>4</td>
<td>4 m</td>
<td>Adhesive wear</td>
</tr>
<tr>
<td>5-7</td>
<td>30-60 cm</td>
<td>Fracture</td>
</tr>
<tr>
<td>8-9</td>
<td>2-3 m</td>
<td>Pin fracture</td>
</tr>
<tr>
<td>10</td>
<td>15 m</td>
<td>Fracture</td>
</tr>
</tbody>
</table>
Recent Tool Life Results

- Tool life is currently in excess of 13 m
- We have turned attention to pursuing welds in a variety of materials
- Fractures continue, but current failure mode is wear due to improper welding parameters
Weld Characterization: Stainless

<table>
<thead>
<tr>
<th></th>
<th>Weld</th>
<th>Base</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield Stress</td>
<td>63 ksi</td>
<td>49 ksi</td>
</tr>
<tr>
<td>UTS</td>
<td>93 ksi</td>
<td>98 ksi</td>
</tr>
<tr>
<td>Elongation</td>
<td>12%</td>
<td>56%</td>
</tr>
</tbody>
</table>
Weld Characterization: High Hard Armor
Stir Features in Weld
Lack of Fusion Defect
Single-Sided Weld
# Properties Summary

<table>
<thead>
<tr>
<th>Coupon #</th>
<th>High Hard 545 rpm 5 1/4 ipm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.2% Yield Stress (ksi)</td>
</tr>
<tr>
<td>1</td>
<td>153.24</td>
</tr>
<tr>
<td>2</td>
<td>150.86</td>
</tr>
<tr>
<td>3</td>
<td>148.07</td>
</tr>
<tr>
<td>Average</td>
<td>150.72</td>
</tr>
<tr>
<td>Stand. Dev.</td>
<td>2.59</td>
</tr>
</tbody>
</table>
Future Plans

- Implement tool thermal instrumentation
- Develop 6.4 mm one-sided weld in High Hard Armor
- Explore DH36, Mild Steel, Titanium, Copper
- Develop tool and operating conditions that work with AL6XN
Summary

- PCBN works well on ferrous materials
  - In excess of 50 feet of weld per tool
- Welds made in variety of materials
  - 3 mm 316 L, 6 mm High Hard Armor successful
  - 6 mm 316L, 6 mm AL6XN need more work
- Custom grades may improve PCBN
  - MN100 has longer life
  - MN50 is easier to make