Progress in Friction Stir Welding High Temperature Materials

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Agenda

- History
- Tool Materials
- Weld Metal Properties
- Materials Welded With PCBN Tools
- Recent Advances
History

- FSW invented in 1991
- Commercial applications in Al alloys
  - Delta rocket casings
  - High-speed ferry decking
  - Automotive components
  - Heat sinks
- ~80% of welded product is steel or stainless steel
- Tool material has been major challenge
Tool Materials-Requirements

- High-temperature strength
- Wear Resistance
- Low Reactivity
- Manufacturability
- Toughness
Tool Materials

- Refractory Metal Alloys
  - Tungsten
  - Molybdenum
  - Tungsten-Rhenium

- Superabrasives
  - Polycrystalline Diamond (PCD)
  - Polycrystalline Cubic Boron Nitride (PCBN)
Tungsten Tools

- Good high-temperature strength
- Poor room-temperature toughness
- Concerns with rapid tool wear

Image from The Welding Institute
Tungsten-Rhenium Tools

- Higher room-temperature toughness (no preheat)
- Improved densification (less wear)
- Some indications of chemical reaction with baseplate
PCBN Tools

- Excellent high-temperature strength
- Abrasion resistant
- Chemically inert

- Limited in size
- Relatively low toughness
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
PCBN Tool Material Grades

- PCBN Properties Vary
  - CBN Particle Size
  - CBN Particle Size Range
  - CBN Fraction
  - Second-phase Material

- Can be Optimized for Welding Specific Materials
PCBN Tool Construction

- Composite tool
  - WC Shank
  - PCBN Insert
  - Nickel-based alloy locking collar to hold tool together
PCBN Tool Performance

- 80 m in A36 steel
- Improved Grades Under Development
  - Specific characteristics for difficult-to-weld alloys
  - Dramatic improvement in AL-6XN
Properties

- Ferritic Steels
  - DH-36
  - 1018
  - S355 C-Mn Steel
  - HSLA-65
  - Quenched and Tempered Steel
- Titanium
- Stainless
  - 304
  - AL-6XN
DH-36

- Full-penetration welds
- Some evidence of tool debris
- Good mechanical properties – weld overmatched compared to base
1018

- Acceptable mechanical properties
- Evidence of tool material in weld
- Fine microstructure near shoulder, coarser away from shoulder
- Temperatures extrapolated to maximum weld-zone temperature of 1200°C
S355 C-Mn Steel

- Weld zone higher strength than base metal
- Second weld tempers first
- Equal low-temperature Charpy values, lower high-temperature Charpy
HSLA-65

- Excellent Mechanical Properties
- Ballistic Testing (Shock-hole Test)
Quenched and Tempered Steel

- Tempering of first pass by second pass
- Softening in HAZ observed
- Compared with GMA welding using carbon steel filler, FSW is stronger but less tough

Data from Paul Konkol, CTC
Titanium

- Ti-17 to Ti-17, Ti-17 to Ti-6-4, Ti-6-2-4-2 to Ti-6-4
- Proprietary tool materials assumed to be W-based
- Strength higher than base material
- Most welds have evidence of tool debris; one tool material, AE-4, shows no visible debris
304 Stainless

- Weld strength higher than base metal
- Refined grain structure in welds
- Dark bands appear to have extra fine grain structure
- Some welds show sigma in fine grain bands
- High strength, excellent ductility
AL-6XN

- Difficult to obtain full consolidation
- Good mechanical properties, even with small hole in weld
- Tool wear a problem
Materials Welded with PCBN

- Ferritic Steels
- Stainless Steels
- Duplex Steels
- Superalloys
- Specialty Alloys
Ferritic Steels

- A-36 / 1018: 80 m tool life
- HSLA-65: 10 m tool life, excellent properties
- X80/X120: Minimal tool wear, good properties
- Quenched and Tempered C-Mn steel: excellent tool life, good properties
- DH-36: Minimal tool wear, excellent properties
- Dual-Ten dual phase – excellent formability
Stainless and Nickel Alloys

- 304
- 2507 Super Duplex
- Alloy 201
- Alloy 600
- Alloy 718
304 Stainless

- Large process window
- Outstanding mechanical properties
- Acceptable tool life – 30 m (100 feet)

- Weld Parameters
  - Rotation: 400 rev/min
  - Travel: 3 in/min
  - Load control: 9,000 lbf
304 Stainless

- Large process window
- Outstanding mechanical properties
- Acceptable tool life – 30 m (100 feet)

Weld Parameters
- Rotation: 400 rev/min
- Travel: 3 in/min
- Load control: 9,000 lbf
Preferentially etched region consists of only grain boundary attack.

Preferentially etched region consists of both heavily etched regions and G.B. attack.

There are holes at the advancing side of friction stir weld in the as-polished condition.
304 Tensile Specimens
2507 Super Duplex Stainless

- Initial parameters only
  - Rotation: 450 rev/min
  - Travel: 3.5 in/min (88 mm/min)
  - Load control: 7400 lbf
2507 Microstructure

Base material (200x)

Center of DXZ (200x)
2507 Phase Composition

**Ferrite : Red**

**Austenite : Green**

![Images showing different phases and grain sizes](image)

![Graph showing grain size vs. distance from initial butt line](graph)
Alloy 201 Weld

- Initial Parameters
  - Rotation: 1000 rev/min
  - Travel: 4 in/min (100 mm/min)

- Tool previously used in alloy 718
Alloy 201 Microstructure

Base material (500x)  TMAZ (50x)  DXZ (500x)
## Alloy 201 Mechanical Properties

### Ni 201 FSW

Transverse Tensile Properties

<table>
<thead>
<tr>
<th>Sample</th>
<th>Yield Strength 0.2 % offset KSI (MPa)</th>
<th>Ultimate Tensile Strength KSI (MPa)</th>
<th>Elongation %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000 RPM, 4 IPM</td>
<td>28 (193)</td>
<td>65 (448)</td>
<td>34</td>
</tr>
<tr>
<td>Base Metal (from literature)</td>
<td>15 (103)</td>
<td>59 (406)</td>
<td>50</td>
</tr>
</tbody>
</table>
Alloy 600 Weld

- Initial Parameters
  - Rotation: 450 rev/min
  - Travel: 2.25 in/min (56 mm/min)
Alloy 600 Microstructure
## Alloy 600 Mechanical Properties

### Alloy 600 FSW

Transverse Tensile Properties

<table>
<thead>
<tr>
<th>Sample</th>
<th>Yield Strength 0.2 % offset KSI (MPa)</th>
<th>Ultimate Tensile Strength KSI (MPa)</th>
<th>Elongation %</th>
</tr>
</thead>
<tbody>
<tr>
<td>450RPM 2 ¼ IPM</td>
<td>54 (374)</td>
<td>104 (719)</td>
<td>27</td>
</tr>
<tr>
<td><em>Base Metal (annealed condition)</em></td>
<td>38 (263)</td>
<td>92 (631)</td>
<td>50</td>
</tr>
</tbody>
</table>
Alloy 718 Weld

- Initial Parameters
  - Rotation: 500 rev/min
  - Travel: 2 IPM

After 4 feet of weld
Alloy 718 Microstructure

Base material (500x)

Center of DXZ (500x)
## Alloy 718 properties

### Alloy 718 FSW

Transverse Tensile Properties

<table>
<thead>
<tr>
<th>Sample</th>
<th>Yield Strength 0.2% offset KSI (MPa)</th>
<th>Ultimate Tensile Strength KSI (MPa)</th>
<th>Elongation %</th>
</tr>
</thead>
<tbody>
<tr>
<td>500 RPM, 2 IPM</td>
<td>97 (668)</td>
<td>143 (986)</td>
<td>16</td>
</tr>
<tr>
<td>Base Metal (Annealed, from literature)</td>
<td>67 (462)</td>
<td>130 (896)</td>
<td>41</td>
</tr>
<tr>
<td>Base Metal (precipitation hardened, from literature)</td>
<td>170 (1172)</td>
<td>202 (1392)</td>
<td>22</td>
</tr>
</tbody>
</table>
Recent Developments

- Specialty alloys
  - Invar
  - Narloy Z

- Underwater welding – demonstrated ability to weld 304 stainless under water without shielding gas; properties being evaluated

- 13 mm pin length – single side weld on 13mm plate

- Pipe Welding – automatic machine for welding of 12” pipe
Summary

- FSW successfully applied to wide variety of iron and nickel alloys
- Properties look good in most cases
  - Low distortion
  - Good strength
  - Reasonable elongation
- Tool life is high enough for high-value applications, and increasing