Friction Stir Welding of API Grade X65 Steel Pipes

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Why FSW of Pipeline Steels

- Ultra high-strength steels
- Properties
- Productivities?
- Hydrogen issue
- Weld metal property matching the base metal
Material

- **API 5L Grade X-65 steel**
  - Common in oil and gas industry for pipelines
  - 0.08C-1.0Mn-0.235Si-0.04Al-0.016Nb
  - $C_{eq} = 0.14$

- **ERW Line Pipe**
  - OD: 12.75” (324 mm)
  - Wall thickness: 0.25” (6.35 mm)
  - Base metal properties per mill specification
    - Yield: 67 ksi
    - Ultimate tensile: 77 ksi
    - Elongation: 33%
Welding

- Polycrystalline cubic boron nitride (PCBN) tool
  - Shoulder diameter: 1”
  - Pin length: 0.22”

- Girth weld
  - Square butt joint configuration
  - No special groove preparation
  - Surface ground before welding
  - Single pass full penetration from OD

- Welding parameters
  - 500 - 600 rpm
  - 4 - 6 in/min
  - Welding forge force: 6500 lbf

- Special run-off tab to eliminate the exit hole on the pipe

- Argon shielding gas from the tool to protect weld from oxidation
Field deployable FSW system
Hydraulic internal support/fixture
Welding movie
Finished pipe
Finished pipe
Microstructure and Mechanical Evaluation

Scale: 1:5

12\times 3.14 = 37.7” Each section: 9” long after metallography samples

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Mechanical Testing

- **Tensile**
  - Room temperature
  - 3 cross-weld tensile: (1-in wide strip) API 1104
  - 3 Base metal at room temperature
    - Orientation: Axial
    - ASTM E8, rectangular flat
    - Full stress strain curve. Yield stress at 0.2% offset plastic strain and at 0.5% total strain

- **Charpy V notch: ASTM E23, 10x5x50 (sub-sized due to wall thickness)**
  - side V-notch through thickness
  - 3 repeats at each temperature.
  - Base metal: axial orientation @ -50, 0, 20C
  - HAZ: @ -50, 0, 20C
  - Weld: @ -50, -30, -20, -10, 0, and 20C
**Tensile properties**

- **Base Metal**

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<tr>
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<tbody>
<tr>
<td>001: L/T Parent</td>
<td>0.2460x 0.2470</td>
<td>0.0508</td>
<td>1.00</td>
<td>66500</td>
<td>78700</td>
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<tr>
<td>002: L/T Parent</td>
<td>0.2350x 0.2470</td>
<td>0.0580</td>
<td>1.00</td>
<td>66300</td>
<td>77500</td>
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<tr>
<td>003: L/T Parent</td>
<td>0.2540x 0.2480</td>
<td>0.0630</td>
<td>1.00</td>
<td>68100</td>
<td>74800</td>
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- **Cross-weld**

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<tbody>
<tr>
<td>004: Cross Weld</td>
<td>1.0300x 0.2470</td>
<td>0.2544</td>
<td>20129.0</td>
<td>Base</td>
<td>Ductile</td>
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<tr>
<td>005: Cross Weld</td>
<td>0.9750x 0.2500</td>
<td>0.2437</td>
<td>18738.0</td>
<td>Base</td>
<td>Ductile</td>
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<tr>
<td>006: Cross Weld</td>
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<td>0.2510</td>
<td>20329.0</td>
<td>Base</td>
<td>Ductile</td>
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Samples failed outside the weld and HAZ during cross-weld tensile test
# Charpy V-Notch Impact Test

<table>
<thead>
<tr>
<th>Charpy Test - ASTM E 23</th>
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<tbody>
<tr>
<td><strong>Position</strong></td>
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<tr>
<td>007: Weld Centre Line</td>
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<td>008: Weld Centre Line</td>
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<td>009: Weld Centre Line</td>
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<td>010: Weld Centre Line</td>
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<td>011: Weld Centre Line</td>
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<tr>
<td>012: Weld Centre Line</td>
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<td>013: HAZ</td>
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<td>014: HAZ</td>
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<tr>
<td>015: HAZ</td>
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<td>016: Parent</td>
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<td>017: Parent</td>
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<td>018: Parent</td>
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</tbody>
</table>

**Item 07**: Percent Shear: 100, 100, 100 / Mils Lat Exp: 88, 85, 91
**Item 08**: Percent Shear: 100, 100, 100 / Mils Lat Exp: 95, 95, 96
**Item 09**: Percent Shear: 100, 100, 100 / Mils Lat Exp: 92, 95, 90
**Item 10**: Percent Shear: 100, 100, 100 / Mils Lat Exp: 97, 98, 96
**Item 11**: Percent Shear: 100, 100, 100 / Mils Lat Exp: 88, 98, 93
**Item 12**: Percent Shear: 100, 100, 100 / Mils Lat Exp: 97, 93, 97
**Item 13**: Percent Shear: 100, 100, 100 / Mils Lat Exp: 94, 98, 88
**Item 14**: Percent Shear: 100, 100, 100 / Mils Lat Exp: 98, 92, 86
**Item 15**: Percent Shear: 100, 100, 100 / Mils Lat Exp: 64, 78, 64
**Item 16**: Percent Shear: 100, 100, 100 / Mils Lat Exp: 82, 84, 83
**Item 17**: Percent Shear: 100, 100, 100 / Mils Lat Exp: 84, 80, 77
**Item 18**: Percent Shear: 100, 100, 100 / Mils Lat Exp: 62, 56, 60
Charpy V-Notch Impact Test

- ASTM E23
- 10×5×50 mm, sub-sized
- All samples showed 100% shear
Weld Cross-Section Macro
The interface is not easily distinguishable under high magnification
Evidence of lack of bonding on the root face

- Relative small ~ 0.15 mm
- Oxide layer
- Did not affect the mechanical tensile and impact properties
Microstructure

Base Metal

05-0488-13  FSW Pipe Section 90 degrees BM

Stir zone

TMAZ

05-0488-10  FSW Pipe Section 90 degrees HAZ
Cross-weld section micro-hardness profile
Summary

- A portable, field deployable FSW system has been developed for successful welding of X65 pipe
- Fully consolidated weld joint can be obtained in a single pass
- Welding speed
- Microstructure/microhardness
- The girth show superior tensile and impact properties