Weld Repair of Manganese Frogs for Enhanced Safety in Shared Service

Marc A. Purslow
Applications Engineer
mpurslow@ewi.org
614.688.5150
Background: Overview

- Austenitic manganese steel (AMS)
  - Highly work-hardenable
  - Resistant to wear
  - High toughness
- Shortest-lived track segments
- Current repair methods cannot restore original durability
- Low interpass temperature requirement limits productivity
- Often repairs cannot be properly completed, causing further damage
Background: Welding AMS

• Temperature of base material must be kept low to retain mechanical properties

• AWS D15.2 specifies a temperature 1 in. (25 mm) from weld of 500°F (260°C)

• Significant variation with manual/semi-automatic processes

• Special welding techniques
  – limit overheating
  – eliminate cracking
  – limit productivity
Background: Breakouts

- Most repairs are of “breakouts”
- Frog casting plastically deforms before fully work-hardening
- Fractures initiate in damaged material
- Broken off when “flowed” material comes in contact with the wheels
- Maintenance grinding is critical

<table>
<thead>
<tr>
<th>Frog Type</th>
<th>1st grinding</th>
<th>2nd grinding</th>
<th>3rd grinding</th>
<th>Steady-state grinding interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-hardened AMS frog</td>
<td>5 MGT</td>
<td>20 MGT</td>
<td>-</td>
<td>20 MGT</td>
</tr>
<tr>
<td>Weld repaired AMS frog</td>
<td>1 day</td>
<td>1 week</td>
<td>1 month</td>
<td>20 MGT</td>
</tr>
</tbody>
</table>
Background: Proposed Processes

- Automated FCAW
  - Higher travel speeds + wire feed speeds = higher productivity
  - More consistent than manual/semi-automatic welding

- Reciprocating Wire Feed (RWF)

- Wire Motion Synchronized with Current Waveform
  - Minimal spatter
  - Low voltage/heat input

RWF current, voltage, and WFS
Objective

• Determine whether automating FCAW process variations can:
  – Improve weld quality
  – Provide quality control
  – Improve productivity
  – Increase repair life
  – Improve ride quality
Approach

• Using #20 frog point “mock-ups”
  – Evaluate current industry repair techniques
  – Evaluate Automated FCAW and RWF FCAW
• Evaluate with mechanical and radiographic testing (RT)
• Select a single automated process
• Develop welding sequence on AMS frog
• Repair 2 AMS frogs
• Evaluate repaired frogs at TTCI
Baseline Welding

- Per AWS D15.2, Handbooks
- Short-circuiting transfer mode
- 35 to 50\(^\circ\) (push) travel angle
- Bead width and length 5/8- and 5-in.
- Bead sequencing
  - Point to heel
  - Stagger craters
  - Avoid side-by-side beads
- Fill craters by reversing direction
- Peen all but first and last layers
- Maximum temperature of 500\(^\circ\) to 600\(^\circ\)F measured 1 in. from weld

<table>
<thead>
<tr>
<th>Process</th>
<th>Electrode Diameter (in.)</th>
<th>Current (A)</th>
<th>Voltage (V)</th>
<th>Travel Speed (ipm)</th>
<th>Heat Input (kJ/in.)</th>
<th>Deposition Rate (lbs/hr.)</th>
<th>Time per Layer (min.)</th>
<th>Thickness per Layer (in.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SMAW</td>
<td>5/32</td>
<td>180</td>
<td>24</td>
<td>4 to 6</td>
<td>45 to 65</td>
<td>3</td>
<td>20</td>
<td>0.045</td>
</tr>
<tr>
<td>FCAW</td>
<td>1/16</td>
<td>200</td>
<td>27</td>
<td>6</td>
<td>60</td>
<td>7 to 8</td>
<td>6.1</td>
<td>0.086</td>
</tr>
</tbody>
</table>
RT/Visual Inspection of Baseline Welds

• SMAW
  – **Heat input:** 60 kJ/in.
  – RT: Scattered porosity throughout
  – Cross section: 2 vertical cracks

• Semi-automatic FCAW
  – **Heat input:** 45 to 65 kJ/in.
  – RT: Scattered porosity
  – Improved quality over SMAW
Interpass Temperature Trials

- SMAW
- #20 Point mock-ups
- No delay between passes
- Industry recommended vs. two EWI sequences
- Staggered long weld beads resulted in lower heat and cycle time
Automated FCAW Trials

• Solid Electrodes Not Commercially Available
  – Self-shielded FCAW Electrode
  – 75% Argon/25% CO₂ Shielding Gas

• Two Parameter Sets
  – Corner Parameters
    • TS: 15 ipm, A: 140, V: 21
    • Heat Input: 12 kJ/in.
    • Corner beads without drooping
  – High-deposition Parameters
    • TS: 15 ipm, A: 200, V: 28
    • Heat Input: 23.5 kJ/in.
Reciprocating Wire Feed Trials

- **Solid Electrodes Not Available**
  - Self-shielded FCAW Electrode
  - 75% Argon/25% CO₂ Shielding Gas

- **Two Parameter Sets Developed**
  - **Corner parameters**
    - Travel Speed: 24 ipm, A: 150, V: 17.5
    - **Heat Input: 7 kJ/in.**
    - Corner beads without drooping
  - **High-deposition Parameters**
    - Travel Speed: 13 ipm, A: 195, V: 18.5
    - **Heat Input: 15.7 kJ/in.**
    - Weave added to promote wetting/tie-in
Tensile Testing of Mock-up Welds

- All YS higher than D15.2 baseline
- All UTS except SA FCAW higher than D15.2 baseline
Hardness

- Higher hardness in automated mock-ups
- May be related to internal heat build-up
  - Less wait time required between passes/layers
Evaluation of Damaged Frog Section

Pores from carbon block weld contamination

Stainless steel butter layer
Partial Frog Repair

- Automated FCAW selected for all subsequent trials
- Previously repaired material removed w/CAG and grinding
- Low and High HI parameters used
## Partial Frog Repair Test Results

<table>
<thead>
<tr>
<th>Property</th>
<th>Typical Casting Properties</th>
<th>Mock-up Material</th>
<th>Baseline SMAW</th>
<th>Baseline SA FCAW</th>
<th>FCAW-A</th>
<th>RWF-FCAW</th>
<th>FCAW-A on Partial Frog (point)</th>
<th>FCAW-A on Partial Frog (wing)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile Strength (ksi)</td>
<td>100 to 145</td>
<td>142</td>
<td>117</td>
<td>96</td>
<td>125</td>
<td>121</td>
<td>112.1</td>
<td>109.5</td>
</tr>
<tr>
<td>Yield Strength (ksi)</td>
<td>50 to 57</td>
<td>59</td>
<td>83</td>
<td>74</td>
<td>83</td>
<td>86</td>
<td>73.7</td>
<td>74.7</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Location</th>
<th>Test Temp. (°F)</th>
<th>Absorbed Energy (J)</th>
<th>Absorbed Energy (ft-lbs)</th>
<th>Lateral Expansion (mm)</th>
<th>Lateral Expansion (mils)</th>
<th>Shear (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Point</td>
<td>-30.28</td>
<td>40.67</td>
<td>30</td>
<td>0.6</td>
<td>23.62</td>
<td>100</td>
</tr>
<tr>
<td>Point</td>
<td>-30.28</td>
<td>43.39</td>
<td>32</td>
<td>0.68</td>
<td>26.77</td>
<td>100</td>
</tr>
<tr>
<td>Point</td>
<td>-30.28</td>
<td>44.74</td>
<td>33</td>
<td>0.44</td>
<td>17.32</td>
<td>100</td>
</tr>
<tr>
<td>Wing</td>
<td>73.4</td>
<td>84.06</td>
<td>62</td>
<td>1.25</td>
<td>49.21</td>
<td>100</td>
</tr>
<tr>
<td>Wing</td>
<td>73.4</td>
<td>115.24</td>
<td>85</td>
<td>1.41</td>
<td>55.51</td>
<td>100</td>
</tr>
<tr>
<td>Wing</td>
<td>73.4</td>
<td>90.84</td>
<td>67</td>
<td>1.34</td>
<td>52.76</td>
<td>100</td>
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</tbody>
</table>
Full-sized Frog Preparation

Photograph of partial frog as-received

Partial frog sections in need of repair in orange

Repaired partial frog sections in green

Repaired full-length frog sections in green
Frog #1 Welding

- Sequence Developed on Partial Frog
- Conformal Frog
  - More prone to cracking defects during weld repairs
  - Crack at heel repaired at EWI
  - Crack in point found after finish-grinding at TTCI
  - Future testing TBD
Frog #1 Welding

Point Welding Sequence

Heel Crack (EWI)

Layers 1-7

Layers 8-11

Layer 14

Layers 12-13 (welded in opposite direction)

Welding Direction

Point Crack (TTCI)
Frog #1 Heel Crack Repair
Frog #2 Welding

• Sequence Developed on Partial Frog
• Flat Frog
  – Less prone to cracking defects during weld repairs
  – No cracks found during welding or finish grinding
• Currently in TTCI’s Test Track
Frog #2 Welding

Step 4: Grinding preparation for taper-fill layer

Step 5: Welding of taper-fill layer
Automation Concept

- Retractable cart
- 6-axis arc welding robot
- 6-axis water-jet cutting robot
- Need for adaptive fill TBD
  - Would require vision system
Frog #2 Testing Results

- Placed in open track in high-tonnage loop (HTL) at Facility for Accelerated Service Testing (FAST)
  - 100-car train
  - 315,000 pound cars
  - 40 miles per hour
Frog #2 Testing Results

- 78.18 MGTs to date
- Maintenance grinding at 10.15 MGTs
  - Bulge in gage face of wing
  - “Flow” length of point
  - HAZ dip in wing
- Maintenance grinding at 17.53 MGTs
  - Gage corners of wing and point
- No visible surface defects or major metal flow
- No additional maintenance grinding has been required
Frog #2 Testing Results: Hardness Data

Wing Hardness

Point Hardness

Location from Point of Frog

<table>
<thead>
<tr>
<th>Location from Point of Frog</th>
<th>Hardness (BHN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>- 16”</td>
<td>800</td>
</tr>
<tr>
<td>- 8”</td>
<td>600</td>
</tr>
<tr>
<td>+ 2”</td>
<td>400</td>
</tr>
<tr>
<td>+ 8”</td>
<td>200</td>
</tr>
<tr>
<td>+ 16”</td>
<td>0</td>
</tr>
<tr>
<td>+ 22”</td>
<td>0</td>
</tr>
</tbody>
</table>

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<thead>
<tr>
<th>Location from Point of Frog</th>
<th>Hardness (BHN)</th>
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<tr>
<td>+ 8”</td>
<td>600</td>
</tr>
<tr>
<td>+ 16”</td>
<td>400</td>
</tr>
<tr>
<td>+ 22”</td>
<td>200</td>
</tr>
</tbody>
</table>

Technologies:
- 0 MGT
- 2 MGT
- 10.15 MGT
- 17.53 MGT
- 42.71 MGT
- 57.46 MGT
- 6.17 MGT
Frog #2 Testing Results: Running Surface Wear

Running Surface Wear
Wing @ 8 in. Past Frog Point

Running Surface Wear
Frog Point @ 32 in. Past Frog Point
Frog #2 Testing Results

- Running surface height loss is relatively uniform
- Deformation rates have stabilized well before maintenance limits are reached
Conclusions

• Automated FCAW can be successfully applied to AMS frogs for:
  – Improved productivity
  – Increased weld quality
  – Lower interpass temperatures

• RWF FCAW
  – Further reduces heat input
  – Equipment is more complex
Conclusions

• Conformal frog required specialized welding techniques to mitigate cracking at interface between the weld repaired area and work-hardened base material.

• In-track testing to date suggests the performance of frogs repaired with automated FCAW is better than those repaired with existing methods.
Acknowledgements

- Work was sponsored by the Federal Railroad Administration of the U.S. Department of Transportation under Contract No. DTFR53-13-C-00037.
- Authors gratefully acknowledge the support and cooperation of Transportation Technology Center, Inc.
- Authors also gratefully acknowledge the support and guidance of CSX Corporation.
References


