Steel Sucker Rod Fatigue Testing – Update on Phase I

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NPS – Norris/AOT
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Background - Goodman Diagram 1926
API Modified Goodman Diagram (MGD)

\[ S_a = \left( \frac{1}{M} + M S_{min} \right) SF \]

\[ S_a = (0.25T + 0.5625 S_{min}) SF \]

\[ S_a = S_{a1} - S_{min} \]

Where:
- \( S_a \) = Maximum Available Stress, PSI (N/mm²)
- \( S_{a1} \) = Maximum Allowable Range of Stress, PSI (N/mm²)
- \( M \) = Slope of \( S_a \) Curve = 0.5625
- \( S_{min} \) = Minimum Stress, PSI (N/mm²) (Calculated or Measured)
- \( SF \) = Service Factor
- \( T \) = Minimum Tensile Strength, PSI (N/mm²)
MGD - API Grade C Rods

![Graph showing minimum tensile strength vs. stress (1000 psi)]
Atlas of Fatigue Curves - 1986

![Graph showing fatigue curves for different conditions.](image)

- **A**: In air
- **C**: In acid brine
- **D**: In acid brine with inhibitor

**Axes:**
- **Y-axis**: Applied Stress (psi)
- **X-axis**: Number of cycles to failure

Legend:
- **E**
- **B**
- **F**
1. Based on improvements in manufacturing techniques and quality, 10,000,000 API cycle life is conservative

2. Instead should expect >50,000,000 cycles
# Nor-Peening® Results – Grade 97

<table>
<thead>
<tr>
<th>Force (lbs)</th>
<th>Stress Amplitude (ksi)</th>
<th>Number of Test</th>
<th>Average Life Cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td>90</td>
<td>89.64</td>
<td>2</td>
<td>27,515</td>
</tr>
<tr>
<td>80</td>
<td>83.12</td>
<td>2</td>
<td>50,782</td>
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<tr>
<td>70</td>
<td>76.60</td>
<td>3</td>
<td>114,787</td>
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<tr>
<td>60</td>
<td>70.08</td>
<td>5</td>
<td>170,005</td>
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<tr>
<td>50</td>
<td>63.56</td>
<td>6</td>
<td>139,482</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Force (lbs)</th>
<th>Stress Amplitude (ksi)</th>
<th>Number of Test</th>
<th>Average Life Cycles</th>
<th>Percent Increase</th>
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</thead>
<tbody>
<tr>
<td>90</td>
<td>89.64</td>
<td>2</td>
<td>62,946</td>
<td>129%</td>
</tr>
<tr>
<td>80</td>
<td>83.12</td>
<td>2</td>
<td>164,748</td>
<td>224%</td>
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<tr>
<td>70</td>
<td>76.60</td>
<td>3</td>
<td>498,713</td>
<td>334%</td>
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<tr>
<td>60</td>
<td>70.08</td>
<td>3</td>
<td>7,702,305</td>
<td>4,431%</td>
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<tr>
<td>50</td>
<td>63.56</td>
<td>1</td>
<td>21,696,977 (NO FAILURE)</td>
<td>INFINITE</td>
</tr>
</tbody>
</table>
Grade 97 Fatigue Curve - Tulsa University
Rotary Bending Fatigue

Average Life Cycles
Nor-Peening® vs. Non-Shot Peened

Stress Amplitude (PSI)

Average Life Cycles

Norris Nor-Peened Test Results
△ Non-Shot Peened Results

09/25-28/2012 2012 Sucker Rod Pumping Workshop
Phase I Testing

• 2 Objectives
  – Nor-Peening® effects on grade 96 rods
  – Comparison benchmark
Bending Fatigue Test Machines

Smaller Tester:
• 4 ft long rod
• ¾” max diameter
• 400 rpm

Larger Tester:
• 8 ft long rods; coupled too
• 1-1/8” max diameter
• 600 to 800 rpm
Grade 96 Peened vs. Unpeened
Fatigue Life Competitor’s Comparison

Performance At 40% Load

<table>
<thead>
<tr>
<th>Rod Grade</th>
<th>Cycles to Failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Norris 96 Peened</td>
<td>200,000</td>
</tr>
<tr>
<td>Norris 97 Peened</td>
<td>170,000</td>
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<tr>
<td>MFG A Special 1</td>
<td>150,000</td>
</tr>
<tr>
<td>MFG A Special 2</td>
<td>140,000</td>
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<tr>
<td>MFG A API D1</td>
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<tr>
<td>MFG A Special 3</td>
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<tr>
<td>MFG A API D 2</td>
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<tr>
<td>MFG A Special 4</td>
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<td>MFG B Special</td>
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<tr>
<td>MFG B API D 1</td>
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<td>MFG B API D 2</td>
<td>60,000</td>
</tr>
<tr>
<td>MFG B API D 3</td>
<td>50,000</td>
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<tr>
<td>MFG C API D</td>
<td>40,000</td>
</tr>
<tr>
<td>MFG C Special</td>
<td>30,000</td>
</tr>
</tbody>
</table>
Phase II - Current Status

- Initiated air fatigue testing of welded, spoolable rods in bend fatigue test machine.
- Started tension-tension (axial) loading of rods in MTS machine to determine if comparison can be obtained between bending fatigue and axial fatigue.
- Partial results show axial – tension/tension has higher fatigue life (as expected) due to less damage than full reverse loading.
Conclusions & Recommendations

- Nor-Peening® proven effective on grades 96 & 97 special high strength rods
- Nor-Peened® fatigue life ~150% to ~1500% greater than compared competitors
- Variation in internal versus external fatigue life results needs further investigation
- MTS air fatigue data and possible correlation will be useful to verify expected life
- Testing needs to continue including corrosion fatigue and connection testing
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