Assessment of Fatigue Life in CuNi Pipe
Fillet Welds & Butt Welds

Prepared for: Babcock Canada
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The Premier Provider of Weld Engineering and Related Service
Introduction to Computational Welding Services

- Grain Size
- Phase Fractions
- Hardness
- Precipitation

THERMAL

- Temp. Dep. Behaviours

Mechanical
- Stress/Strain State
- Failure
  - Hot Cracking
  - Ductility Cracking
  - Creep
  - Fatigue

Microstructure

Deformation

1 2 3 4 5 6
A Real Example: Repair a Cracked Drum
Repair a Cracked Drum

Martensite Formation

Martensite Map
Practical Microstructure Modeling of Welding for Perfect Weld

Repair a Cracked Drum

Bainite Map

Pearlite Map

Ferrite Map

Hardness Map
Repair a Cracked Drum

Distortion 10X
Grid: Original Position
Repair a Cracked Drum

Residual Stress
(Effective Stress)
Repair a Cracked Drum

Residual Stress (Longitudinal Stress)

Residual Stress (Transverse Stress)
Repair a Cracked Drum

Plastic Strain
Assessment of Fatigue Life in CuNi Pipe – Babcock Canada
Precipitation

Failure

Deformation

Stress/Strain State

- Hot Cracking
- Ductility Cracking
- Creep

- Fatigue

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Assessment of Fatigue Life in CuNi Pipe – Babcock Canada

Mechanical

- Stress/Strain State
- Failure
- Fatigue
  - Hot Cracking
  - Ductility Cracking
  - Creep

Fillet Welds
- 211 HSD W1&W2
- 911 BB W4a

Butt Welds
- 911 BB W3
- 923 BB W4
Problem Definition: Copper-Nickel Alloy 70/30
ASTM/UNS C71500

<table>
<thead>
<tr>
<th>Designation</th>
<th>211 HSD – W1 &amp; W2</th>
<th>911 BB W4a</th>
<th>923 BB W4</th>
<th>911 BB W3</th>
</tr>
</thead>
<tbody>
<tr>
<td>System</td>
<td>Hydraulic</td>
<td>Air</td>
<td>Air</td>
<td>Air</td>
</tr>
<tr>
<td>Medium</td>
<td>Air</td>
<td>Air</td>
<td>Air</td>
<td>Air</td>
</tr>
<tr>
<td>Working Pressure</td>
<td>280 bar</td>
<td>280 bar</td>
<td>280 bar</td>
<td>280 bar</td>
</tr>
<tr>
<td>od</td>
<td>20 mm</td>
<td>30 mm</td>
<td>30 mm</td>
<td>30 mm</td>
</tr>
<tr>
<td>p</td>
<td>3.5 mm</td>
<td>5 mm</td>
<td>5.37 mm</td>
<td>5.7 mm</td>
</tr>
<tr>
<td>s</td>
<td>6 mm</td>
<td>7.5 mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>w</td>
<td>8.75 mm</td>
<td>12.5 mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>h</td>
<td>5 mm</td>
<td>7.5 mm</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fillet Welds
- 211 HSD W1&W2
- 911 BB W4a

Butt Welds
- 911 BB W3
- 923 BB W4
## Flaws Definition:

<table>
<thead>
<tr>
<th>Pipe Designation</th>
<th>Defect Designation</th>
<th>Defect Type</th>
<th>Dimensions (mm)</th>
<th>Defect Location (mm)</th>
<th>Allowable Size (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>211HSD W1</td>
<td>211HSDW1 – P1</td>
<td>P</td>
<td>Ø 1.5</td>
<td>h 4 d 1 α 90°</td>
<td>Ø 0.7</td>
</tr>
<tr>
<td>211HSD W1</td>
<td>211HSD W1 – LOF1</td>
<td>LOF</td>
<td>H 0.075, L 7, D 0.25*</td>
<td>α 96° – 138°</td>
<td>None</td>
</tr>
<tr>
<td>211HSD W2</td>
<td>211HSD W2 – OP1</td>
<td>OP</td>
<td>a 0.3 b 1.2</td>
<td>h 5 d 2 α 190°</td>
<td>b 0.8 mm</td>
</tr>
<tr>
<td>211HSD W2</td>
<td>211HSD W2 – OP2</td>
<td>OP</td>
<td>a 0.375 b 0.75</td>
<td>h 2 d 4 α 200°</td>
<td>b 0.8 mm</td>
</tr>
<tr>
<td>911BB W4a</td>
<td>411BB W4a – P1</td>
<td>P</td>
<td>Ø 1.5</td>
<td>h 5 d 6 α 288°</td>
<td>Ø 1</td>
</tr>
<tr>
<td>911BB W4a</td>
<td>411BB W4a – P2</td>
<td>P</td>
<td>Ø 1</td>
<td>h 7 d 5 α 282°</td>
<td>Ø 1</td>
</tr>
<tr>
<td>911BB W4a</td>
<td>411BB W4a – P3</td>
<td>P</td>
<td>Ø 1</td>
<td>h 8 d 4 α 198°</td>
<td>Ø 1</td>
</tr>
<tr>
<td>911BB W4a</td>
<td>411BB W4a – P4</td>
<td>P</td>
<td>Ø 1</td>
<td>h 6 d 5 α 192°</td>
<td>Ø 1</td>
</tr>
<tr>
<td>911BB W4a</td>
<td>411BB W4a – P5</td>
<td>P</td>
<td>Ø 0.5</td>
<td>h 3 d 2.5 α 186°</td>
<td>Ø 1</td>
</tr>
<tr>
<td>911BB W4a</td>
<td>411BB W4a – P6</td>
<td>P</td>
<td>Ø 1</td>
<td>h 4 d 0 α 276°</td>
<td>Ø 1</td>
</tr>
<tr>
<td>923 BB W4</td>
<td>923 BB W4 – P1</td>
<td>P</td>
<td>Ø 1.5</td>
<td>r 0 z 0.3 θ 0°</td>
<td>Ø 1.1</td>
</tr>
<tr>
<td>923 BB W4</td>
<td>923 BB W4 – P2</td>
<td>P</td>
<td>Ø 1.0</td>
<td>r 3.9 z 2.5 θ 90°</td>
<td>Ø 1.1</td>
</tr>
<tr>
<td>923 BB W4</td>
<td>923 BB W4 – P3</td>
<td>P</td>
<td>Ø 1.0</td>
<td>r 3.9 z 1.5 θ 90°</td>
<td>Ø 1.1</td>
</tr>
<tr>
<td>923 BB W4</td>
<td>923 BB W4 – BT1</td>
<td>BT</td>
<td>a 2.5 b 5</td>
<td>r 0 z 0 θ 90°</td>
<td>None</td>
</tr>
<tr>
<td>923 BB W4</td>
<td>923 BB W4 – LOF1</td>
<td>LOF</td>
<td>L 7 d 1 w 0.4</td>
<td>r 0 z 1 θ -5°</td>
<td>None</td>
</tr>
<tr>
<td>911BB W3</td>
<td>911 BB W3 – P1</td>
<td>P</td>
<td>Ø 1.5</td>
<td>r 4.3 z 0 θ 0°</td>
<td>Ø 1</td>
</tr>
</tbody>
</table>

Convention for naming and dimensioning defects
Material Property Used:

ASTM E8/E8M-13a

ASTM E468

ASTM E647-13a
Introduction to Fatigue:

Energy-based vs. Mechanical-based

Energy Level at Material (Load, Temp, Work, ...)

- Elastic Deformation
- Plastic Deformation
- Separation/Surface formation
- Metallurgical Phase transformation
- Diffusion and Migration
- Grain Boundary Sliding
- Electrochemical Degradation
- Others

Energy Consuming Mechanisms
Fatigue Mechanisms;

- Fatigue Crack Initiation Mechanism

Generally, the greatest portion of the fatigue life is spent nucleating and growing a fatigue crack to a length at which it can be detected (i.e. short-crack propagation).

Safe Life Design Approach

- Fatigue Crack Growth Mechanism

Sub-critical (stable) crack growth is used in combination with the initiation life to predict the total life i.e. reaching dysfunctional length.

Damage Tolerance Design Approach

DT can be used for prediction of RUL from an initial crack or crack-like defect.
Old-Fashion Approximation of Safe Life:

1. Analytical stress approximation
2. Use empirical relation to define notch effect $K_t$, i.e. stress concentration factor, based on similarity of flaw shape
3. S-N curve to estimate safe-life

**Main Limitation:**
- Analytical eqs are not accurate representative of actual stress map
- Defining $K_t$ is subjective, based on similarity of flaw shapes
- You have to have material S-N curves for variety of $K_t$ (Fatigue’s inherent deviation, reading log-log plot, long time, high cost)
- Cannot define CCL
State-of-the-Art Safe Life Analysis;

Step 1. Computing Exact Stress Map by FEA at all Levels of Loading Complexity

Stress Maps for 211HSD – W1 & W2
State-of-the-Art Safe Life Analysis;

Step 1. Computing Exact Stress Map by FEA at all Levels of Loading Complexity

Stress Maps for 923 BB W4
State-of-the-Art Safe Life Analysis;

Step 1. Computing Exact Stress Map by FEA at all Levels of Loading Complexity

Stress Maps for 911 BB W4a
State-of-the-Art Safe Life Analysis;

Step 1. Computing Exact Stress Map by FEA at all Levels of Loading Complexity

Stress Maps for 911 BB W3
State-of-the-Art Safe Life Analysis;

No need to additional $K_t$ calculation, It is already built-in the FEA since the stress is computed finely for given geometry including flaw’s geometry.
State-of-the-Art Safe Life Analysis;

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State-of-the-Art Safe Life Analysis;

Step 2. Computing Safe Life everywhere using computational representative of single S-N curve (No notch, the most feasible available) as oppose to reading from plot.

\[ \sigma_f = 2480.093, \quad b = -0.13958, \quad \varepsilon_f = 0.5645, \quad c = -0.536 \]
State-of-the-Art Safe Life Analysis;

Step 2. Computing Safe Life everywhere using computational representative of single S-N curve (No notch, the cheapest) as oppose to reading from plot.

* Location of CCL (shortest life)

<table>
<thead>
<tr>
<th>Location</th>
<th>Pressure Cycle (bar)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location</td>
<td>0 to 280</td>
</tr>
<tr>
<td>LOF tip close to porosity</td>
<td>7,600</td>
</tr>
<tr>
<td>LOF tip away from porosity</td>
<td>12,600</td>
</tr>
<tr>
<td>Pipe/sleeve gap close to porosity</td>
<td>17,600</td>
</tr>
<tr>
<td>Pipe/sleeve gap away from porosity</td>
<td>19,500</td>
</tr>
</tbody>
</table>
State-of-the-Art Safe Life Analysis;

Step 2. Computing Safe Life everywhere using computational representative of single S-N curve (No notch, the cheapest) as oppose to reading from plot.

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<table>
<thead>
<tr>
<th>Location</th>
<th>Pressure Cycle</th>
</tr>
</thead>
<tbody>
<tr>
<td>923 BB W4 – P1</td>
<td>1,500,000</td>
</tr>
<tr>
<td>923 BB W4 – P2 &amp; P3</td>
<td>&gt; 10^7</td>
</tr>
<tr>
<td>923 BB W4 – BT1</td>
<td>2,500,000</td>
</tr>
<tr>
<td>923 BB W4 – LOF1</td>
<td>2,500,000</td>
</tr>
</tbody>
</table>
Crack Propagation and Growth Analysis;

Classical Fracture Mechanics;  
\[ K = \beta \sigma \sqrt{\pi a} \]

\( K \): Stress Intensity Factor (SIF)  
\( \beta \): Factor of flaw shape 
\( \sigma \): Nominal or design stress 
\( a \): Flaw size

Fracture happens if \( K = K_c \) (Material toughness)

Fatigue Fracture;

Crack growth rate (per cycle)
State-of-the-Art Damage Tolerance Analysis;

Step 1. Introducing an Initial Crack

- Location: CCL
- Direction of growth and opening

Mechanics of growth; Normal to the local stress contours

Principal stress, X Y Z tensor - misleading
911 BB W3

Hoop

Axial

Radial
What about the new stress rise at the tip of crack?

911 BB W3
Manually inserting a 10 grain size (0.5 mm) crack at CCL directed as determined.

Repeat stress-strain calculation and new direction for next increment of growth

So on so forth until dysfunctional length
211 HSD W1 – P1

Effect from close by flaw

Growth direction switches
State-of-the-Art Damage Tolerance Analysis;

Step 2. Time (or cycle) Computation

Definition and Concept
Strain Energy Release Rate; $G$

$$G := \left[ \frac{\partial U}{\partial a} \right]_P = - \left[ \frac{\partial U}{\partial a} \right]_u$$

Non-linear case:

$$J = \int_{\Gamma} (w \, dy - T_i \frac{\partial u_i}{\partial x} \, ds) \quad \text{with} \quad w = \int_0^{\varepsilon_{ij}} \sigma_{ij} \, d\varepsilon_{ij}$$

$$G = K_I^2 \left( \frac{1 - \nu^2}{E} \right) + K_{II}^2 \left( \frac{1 - \nu^2}{E} \right) + K_{III}^2 \left( \frac{1}{2\mu} \right).$$
State-of-the-Art Damage Tolerance Analysis;

Step 2. Time (or cycle) Computation

SIF is computed by FEA J-integral integration for every increment of crack growth
State-of-the-Art Damage Tolerance Analysis;

Step 2. Time (or cycle) Computation

![Graphs showing crack growth data for Cu-Ni pipes under different conditions.](image)
Assessment of Fatigue Life in CuNi Pipe – Babcock Canada

Short-Crack Propagation Analysis;
## Fatigue Life Perdition Summary;

### 211 HSD W1 & W2

#### Nucleation

<table>
<thead>
<tr>
<th>Location</th>
<th>Pressure Cycle (bar)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOF tip close to porosity</td>
<td>0 to 280</td>
</tr>
<tr>
<td>LOF tip away from porosity</td>
<td>0 to 207</td>
</tr>
<tr>
<td>Pipe/sleeve gap close to porosity</td>
<td>176 to 207</td>
</tr>
<tr>
<td>Pipe/sleeve gap away from porosity</td>
<td>176 to 207</td>
</tr>
</tbody>
</table>

#### Growth

<table>
<thead>
<tr>
<th>Pressure Cycle (bar)</th>
<th>Cycles to grow crack to dysfunctional length</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 to 280</td>
<td>185,000</td>
</tr>
<tr>
<td>0 to 207</td>
<td>888,000</td>
</tr>
</tbody>
</table>

### 923 BB W4

#### Nucleation

<table>
<thead>
<tr>
<th>Location</th>
<th>Pressure Cycle (bar)</th>
</tr>
</thead>
<tbody>
<tr>
<td>923 BB W4 – P1</td>
<td>0 to 280 bar</td>
</tr>
<tr>
<td>923 BB W4 – P2 &amp; P3</td>
<td>&gt; 10⁷</td>
</tr>
<tr>
<td>923 BB W4 – BT1</td>
<td>2,500,000</td>
</tr>
<tr>
<td>923 BB W4 – LOF1</td>
<td>2,500,000</td>
</tr>
</tbody>
</table>

#### Growth

<table>
<thead>
<tr>
<th>Pressure Cycle (bar)</th>
<th>Cycles to grow the crack from 0.5 mm to 1 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 to 280</td>
<td>100,000</td>
</tr>
</tbody>
</table>
**Sensitivity Analysis**

<table>
<thead>
<tr>
<th>Analysis Number</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size (Diam - mm)</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>1.5</td>
<td>1.5</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Location*</td>
<td>1.425</td>
<td>2.85</td>
<td>4.275</td>
<td>1.425</td>
<td>2.85</td>
<td>4.275</td>
<td>1.425</td>
<td>2.85</td>
<td>4.275</td>
</tr>
</tbody>
</table>

* Distance from pore's centre and pipe's inner surface - mm

911 BB W3
Assessment of Fatigue Life in CuNi Pipe – Babcock Canada
Flaw Location more important than Size;  

A comparative stress analysis was carried out considering the following three scenarios:

1. The **perfect weld** with no-flaws to give a standard reference as to the levels of stress to be usually expected in the as designed state
2. The weld with included **actual** defects.
3. The weld with defects resized to be **acceptable** as per DEF-STAN.

![Perfect Weld](image_url)
Flaw Location more important than Size; 911BB – W4a
Summary;

<table>
<thead>
<tr>
<th></th>
<th>Sleeve &amp; Socket Weld</th>
<th>Butt Weld</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Static Strength</strong></td>
<td>Stresses are below yield strength in most cases.</td>
<td>Stresses are below yield strength in most cases.</td>
</tr>
<tr>
<td><strong>Fatigue</strong></td>
<td>Porosity can cause notable stress concentrations if close to the root or pipe wall (toe). Only porosity close to the root attains the stress levels necessary for yielding thus crack nucleation and growth. Crack growth is however extremely slow. Lack of Root Fusion causes a crack growth life of 185,000 cycles for HP Air and 888,000 cycles for Hydraulics.</td>
<td>Porosity on the inner surface (surface defect) leads to high stress concentrations that can be critical. Otherwise porosity can cause stress concentrations if close to the root but does not result in a limiting fatigue life. Lack of root fusion, burn through and internal surface defects are of approximately equal criticality and cause a crack nucleation life in excess of 1,500,000 cycles and crack growth life of 100,000 cycles for HP Air.</td>
</tr>
</tbody>
</table>
Thank You

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Figure B.1 — Assessment methodology for fatigue crack growth in tubular joints
Obtaining the Perfect Weld Using Welding Simulation and Models