Magnetic Barkhausen Noise Response to Temper Embrittlement of HY–80 Steel

Aroba Saleem¹, Ross Underhill¹, Nancy Herve², Shannon P. Farrell² and Thomas Krause¹

¹Department of Physics and Space Science, Royal Military College of Canada
²Dockyard Laboratory (Atlantic), Defence Research and Development Canada
Applications
Challenges

- Saline water – 35,000 ppm
- Water temperatures – vary widely with latitude
- Temperature gradient – water temperature decreases with depth
- Other factors – exhaust ports, welding regions
Material requirements for submarine applications

- Corrosion resistance

- Stable physical properties
  - High strength-to-weight ratio
  - High modulus of elasticity
  - High toughness
  - Resistance to fatigue
Problem

- Temper Embrittlement – decrease of impact toughness
- Intergranular failure
- Occurs during post fabrication heat treatment
- Change of ductile-to-brittle transition temperature
  - Ductile-to-brittle transition temperature of HY-80 is $-18 \, ^\circ\text{C}$
- Measurement of temper embrittlement – destructive testing
Failure due to brittle fracture

- Freezing temperature
- Impact loading
- Sulphur content
- Brittle fracture
Magnetic Barkhausen Noise Analysis

- Discontinuous magnetization changes – changing applied magnetic fields
  - Abrupt magnetic domain wall motion

- Sensitive to microstructural variations and stress state of material
  - Grain size, texture, inclusions
  - Strength and hardness

- Potential non-destructive testing (NDT) method
Magnetic Barkhausen Noise Analysis

\[ MBN_{\text{Energy}} = \sum_{\text{events}} \int V^2 \, dt \]

Krause et al., Micromagnetic Techniques, ASM Handbook, 2018
Temper Embrittlement

Magnetic Properties
- Magnetic Domains
- Hysteresis loop
- MBN energy

SEM

Microstructure
- Grain size
- Precipitates
- Texture
- Phases
- Composition

EDS

XRD

EBS

Mechanical Properties
- Toughness
- Hardness

MBN

Vickers Microhardness test

Impact test
# Materials and Methodology

<table>
<thead>
<tr>
<th></th>
<th>Dimensions</th>
<th>Holding time at 525°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample 1</td>
<td>114.7 mm × 69.3 mm × 5.2 mm</td>
<td>48 hrs</td>
</tr>
<tr>
<td>Sample 2</td>
<td>120.4 mm × 69.2 mm × 5.2 mm</td>
<td>168 hrs</td>
</tr>
<tr>
<td>Sample 3</td>
<td>129.9 mm × 69.3 mm × 5.3 mm</td>
<td>336 hrs</td>
</tr>
</tbody>
</table>
Materials and Methodology

Magnetic Barkhausen Noise (MBN) Measurement

- Tetrapole probe
- Flux controlled (350 mT)
- 50 Hz

S. A. White, “A Barkhausen Noise Testing System for CANDU Feeder Pipes”, Queen’s University, 2018
Materials and Methodology

Impact testing

Impact tester

Energy absorbed until fracture (Toughness)

Sample before testing

Sample after fracture

Materials and Methodology

Hardness testing

Vickers microhardness tester

Surface 1

Surface 2 (bottom surface)

Top view

Cross-section

Indents
**Concept map**

- **Magnetic Properties**
  - Magnetic Domains
  - Hysteresis loop
  - MBN energy

- **Temper Embrittlement**

- **SEM**
- EDS
- XRD
- EBSD

- **Microstructure**
  - Grain size
  - Precipitates
  - Texture
  - Phases
  - Composition

- **Mechanical Properties**
  - Toughness
  - Hardness

- **Vickers Microhardness test**
- Impact test

- **MBN**
MBN Results – Sample 1

MBN energy at 0°

Peak $V_{MBN}$

Angle = 0°
MBN Results – Sample 2

MBN energy at 0°
MBN Results – Sample 3

MBN Energy (mV²s) vs. Angle

MBN energy at 0°

Peak $V_{MBN}$

Angle = 0°
Effect of holding time

\[
y = 300.59 \times \exp(-t/160.29) + 423.92
\]

\[
y = 239.9 \times \exp(-t/192.84) + 206.84
\]
Temper Embrittlement

- Magnetic Properties
  - Magnetic Domains
  - Hysteresis loop
  - MBN energy

- Mechanical Properties
  - Toughness
  - Hardness

- Microstructure
  - Grain size
  - Precipitates
  - Texture
  - Phases
  - Composition

- TEM
  - SEM

- Analysis Techniques
  - EDS
  - XRD
  - EBSD

- Test Methods
  - Vickers Microhardness test
  - Impact test
SEM Microstructure

- Ultrafine carbides
- Acicular ferrite
- Soft matrix (low carbon)
- Carbon rich plate boundaries

NDT in Canada 2018 | June 19–21 | Halifax, NS
SEM Microstructure

<table>
<thead>
<tr>
<th></th>
<th>Soft Ferrite Matrix (µm)</th>
<th>Acicular ferrite (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample 1</td>
<td>9 ± 2</td>
<td>1.9 ± 0.46</td>
</tr>
<tr>
<td>Sample 2</td>
<td>17 ± 3</td>
<td>2.68 ± 0.64</td>
</tr>
<tr>
<td>Sample 3</td>
<td>15 ± 1.8</td>
<td>2.3 ± 0.569</td>
</tr>
</tbody>
</table>

- Crystallite size increases with holding time – MBN energy decreases
- Carbides distributed throughout the matrix (EDS)
- With increase in holding time, carbides segregate near the boundaries and increase in size – soft matrix
X-Ray Diffraction

<table>
<thead>
<tr>
<th>Ferrite peak (110)</th>
<th>Sample 1</th>
<th>Sample 2</th>
<th>Sample 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>2θ = 44.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FWHM</td>
<td>0.20</td>
<td>0.15</td>
<td>0.16</td>
</tr>
</tbody>
</table>
Concept map

**Temper Embrittlement**
- Magnetic Domains
- Hysteresis loop
- MBN energy

**Magnetic Properties**

**Microstructure**
- Grain size
- Precipitates
- Texture
- Phases
- Composition

**SEM**

**Mechanical Properties**
- Toughness
- Hardness

**XRD**

**EDS**

**EBSD**

**MBN**

**Vickers Microhardness test**

**Impact test**
Impact energy

\[ y = 42.30 \times \exp\left(-\frac{t}{231}\right) + 18.138 \]
Impact energy vs MBN energy

Average MBN energy for Surface 1 and Surface 2

\[ y = 162.1169 + 6.7829 \times \]
Hardness – cross section

\[ y = 238.521 + (-1/110) x \]

Surface 1 edge

Surface 2 edge

Sample cross-section

Indents
Hardness vs MBN energy

Average MBN energy from Angle = 0° to 360°
Hardness – cross section

- Carbide segregation near Surface 1 results in higher hardness near Surface 1 than Surface 2
- Carbides uniformly distributed – pinning – MBN energy isotropic for Surface 1
- Texture effect on MBN more dominant than carbide effect – Surface 2

*Krause et al., Micromagnetic Techniques, ASM Handbook, 2018*
Summary

MBN signal decreases exponentially

- Increase in Crystallite size
- Carbides – near the boundaries – soft matrix
- Migration of trace elements towards grain boundaries (P, Sn, As)

MBN energy ↔ Toughness

- Carbide segregation near surface 1 – pinning effect
- Hardness higher for Surface 1
- Texture effects – Surface 2
Acknowledgements

CDARP
(Canadian Defence Academy Research Program)
Thank you